GEOLOGY AND TERRANE RELATIONSHIPS OF THE TAR RIVER AREA, FRANKLIN AND GRANVILLE COUNTIES, NORTH CAROLINA

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ABSTRACT

Geologic mapping and geochemical analysis indicate that metaigneous rocks of the Tar River area in the eastern North Carolina Piedmont share similar lithologic and major trace element attributes that are compatible with an origin in a late Proterozoic to Cambrian, peri-Gondwanan, calc-alkaline island-arc known as the Carolina Zone. The results of structural analyses indicate that these rocks experienced a complex tectonothermal history that spans the late Proterozoic into the early Mesozoic.

The metaigneous rocks are grouped into two structural domains that encompass four lithotectonic terranes on the western flank of the Alleghanian Wake-Warren anticlinorium. Western Domain I includes the Carolina terrane, which primarily contains the Gibbs Creek metatonalite pluton. This pluton hosts greenstone, amphibolite, metaultramafic, and metagranitoid enclaves that experienced a greenschist to amphibolite facies metamorphism (M_e) prior to their inclusion in the pluton. Amphibolite and metagranitoid retain an S_e foliation that possibly represents a pre-Taconic (D_e) deformation. The Gibbs Creek pluton is in contact with a small metagranodiorite pluton along its eastern edge and is crosscut by a map-scale metagabbro dike. The Ruin Creek Gneiss defines the eastern limits of Domain I and is a mylonitic granitic gneiss that may represent a deformed late Paleozoic intrusion.

Domain II includes the Falls Lake, Crabtree, and Raleigh terranes. The Falls Lake terrane contains a biotite white mica schist, the Falls Lake Schist and bodies of metaultramafic rocks. The Crabtree terrane contains interlayered felsic, intermediate, and mafic gneiss known as the Middle Creek Gneiss and Middle Creek Amphibolite, and

more minor blocks of metaultramafic rocks. The Raleigh terrane contains interlayered felsic, intermediate, and mafic gneiss known as the Raleigh Gneiss and the Falls Leucogneiss, and also includes more minor bodies of metaultramafic rocks. The Wilton granite pluton and two smaller foliated granitic bodies are late Paleozoic intrusions that intrude all terranes of Domain II.

The metaigneous rocks experienced a Taconic greenschist facies M_1 metamorphism that is related to the collision between the Carolina Zone and Laurentia and is only preserved within Domain I. An Alleghanian amphibolite facies M_2 metamorphism affected the rocks within Domain II. M_2 was accompanied by a D_3 deformation that affected both domains during the transpressional collision between Laurentia and Gondwana and the formation of Pangea. D_3 produced a northeast-striking S_1 mylonite foliation, subhorizontal L_1 stretch lineation, and minor F_1 folds along with small ductile dextral faults and the larger terrane bounding Falls Lake and Nutbush Creek fault zones.

The western portions of Domain I also preserve several D_4 ductile-brittle normal faults that contain a northeast-striking S_2 phyllonite foliation and L_2 dip-parallel stretch lineation. D_4 deformation also produced a major terrane-bounding brittle normal fault, the Jonesboro fault, which separates the Domain I graben from Domain II horst and highlights the distinct metamorphic discontinuity between rocks on either side of the fault. The formation of the Jonesboro normal fault, combined with the intrusion of Jurassic-age diabase dikes that crosscut all terranes within the Tar River area, are attributed to the initial breakup and rifting of the Pangean supercontinent.

ACKNOWLEDGMENTS

The author thanks the EDMAP program for the initial funding for this project. The Southeastern Section of the Geological Society of America provided funding for fieldwork. The North Carolina State Survey provided additional funding for geochemistry. I also thank Tyler Clark and Mike Medina at the North Carolina State Survey for their comments and assistance with digitizing my geologic map. This project could not be completed without the guidance, support, and funding from my thesis advisor, Dr. David E. Blake. I thank my committee members Dr. John R. Huntsman and Dr. Michael S. Smith for their guidance and support. Additional advice and guidance was provided by Dr. Edward F. "Skip" Stoddard at North Carolina State University. I thank all the faculty and staff in the Department of Earth Sciences at the University of North Carolina at Wilmington for their help and support over the years. I cannot say enough about the support given to me from my many friends here at UNCW. These friends have really been close, Cindy Phillips, Kelley Kaltenbach, Ben Grosser, Maverick Raber, John Huntley, Chester "CJ" Jackson, and Beth Reimer. Lastly, I thank my family for their love, support, and always being there when I need them.

DEDICATION

I dedicate this thesis to my parents, Henry and Beth Robitaille, whose financial and moral support and their love throughout the years have helped me progress to this point.

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INTRODUCTION

The geology of the eastern Piedmont of North Carolina has been under scrutiny the past 30 years (Hatcher and others, 1977; Parker, 1979; Farrar, 1985a,b; Stoddard and others, 1991; Hibbard and Samson, 1995; Hibbard and others, 2002). Changes to our views of regional tectonics, along with better methods of rock analysis and age dating, have led to redefined ideas on its geologic history. The United States Geological Survey (USGS) and the National Congressional Geologic Mapping Program (NCGMP) under auspices of the North Carolina Geological Survey (NCGS) have funded STATEMAP and EDMAP projects. Researchers from various universities have benefited from these STATEMAP and EDMAP projects and have provided local geologic mapping data. This study of the Tar River area is an EDMAP project (98HQAG2100) funded through the USGS and is part of a North Carolina Geological Survey STATEMAP project in the Henderson 100K topographic quadrangle. This study provides refined data from geological mapping on a 7.5-minute scale in the Franklinton, Grissom, Kittrell, and Wilton topographic quadrangles.

Regional Geologic Setting

The eastern Piedmont of North Carolina is the product of a long history of tectonic development. A volcanic island-arc of peri-Gondwanan affinity formed in a subduction-related environment during the late Proterozoic to early Paleozoic (Nance and Thompson, 1996; Hibbard and Samson, 1995; Hibbard, 2000; Hibbard and others 2002). This volcanic island-arc contained late Proterozoic to early Cambrian plutonic, volcanic, volcanoclastic, and sedimentary rocks and an Acado-Baltic fauna that is considered to be exotic to Laurentia (Samson and others, 1990; Hibbard and Samson, 1995; Hibbard and others, 2002). The volcanic island-arc collided and accreted with Laurentia during the Taconic orogeny, resulting in a regional greenschist facies metamorphism of these rocks (Rankin and others, 1989; Butler and Secor, 1991; Hibbard, 2000).

Subsequent collision of Gondwana with Laurentia during the Alleghanian orogeny produced a regional amphibolite facies metamorphism, ductile dextral faults, major and minor folds, and plutonism that overprinted metamorphic and structural features on parts of the volcanic island-arc. This volcanic island-arc was first categorized and separated into the belt terminology of King (1955, 1959), Parker (1968), and Rodgers (1970). The North Carolina eastern Piedmont was subdivided into the Carolina slate belt, the Raleigh metamorphic belt, and the Eastern slate belt on the basis of regional metamorphic grade (Stoddard and others, 1991).

Horton and others (1989) suggested a more precise subdivision of the belts into terranes based on the grade of metamorphism and a system of bounding anastomosing ductile dextral faults known as the Eastern Piedmont fault system (Hatcher and others, 1977). A terrane is a fault-bounded body of rock of regional extent, characterized by a geologic history different from that of contiguous terranes or bounding continents. A terrane is generally considered to be a discrete allochthonous fragment of oceanic or continental material added to a craton at an active margin by accretion (Jackson, 1997). In the Raleigh metamorphic belt or Wake-Warren anticlinorium, the Eastern Piedmont fault system juxtaposed a series of terranes that Horton and others (1989) and Stoddard and others (1991) called the Carolina, Falls Lake, Crabtree, Raleigh, Spring Hope, and

Roanoke Rapids terranes (Figure 1). Hibbard and Samson (1995), using Williams' (1976, 1978) zonal subdivision of the Appalachian orogen from the Newfoundland sector, grouped these terranes into the "Carolina Zone" based on their volcanic island-arc affinity and rock assemblages. The term "zone" indicates a division of the orogen that allows for recognition of global-scale elements not immediately evident at the terrane level (Hibbard and Samson, 1995).

The Wake-Warren anticlinorium contains a variety of metaplutonic, metavolcanic, metasedimentary, and plutonic rocks in several amalgamated terranes. The terranes are arranged in a structural stack that includes the structurally higher Carolina, Spring Hope, and Roanoke Rapids terranes, and the structurally lower Falls Lake, Crabtree, Raleigh, and Triplet terranes (Figure 1). Faults associated with the Eastern Piedmont fault system bound each of the terranes. The major fault zones in the Wake-Warren anticlinorium bounding these terranes are the Leesville, Falls Lake, Nutbush Creek, Lake Gordon, and Hollister faults (Figure 1). These are primarily ductile dextral faults with the exception of the Falls Lake fault, which displays some thrust elements (Stoddard and others, 1994). The Macon fault also displays elements of being a ductile thrust (Sacks, 1999). Macroscale and mesoscale folds are also associated with the Alleghanian tectonothermal metamorphism. The Wake-Warren anticlinorium is a major fold with its hinge zone exposing the highest grade rocks and its limbs are the western and eastern flanks, which decrease in metamorphic grade. The Raleigh antiform, Lake Royal antiform, Smithfield synform, and Spring Hope synform, are folds on the limbs of the Wake-Warren anticlinorium (Figure 1).

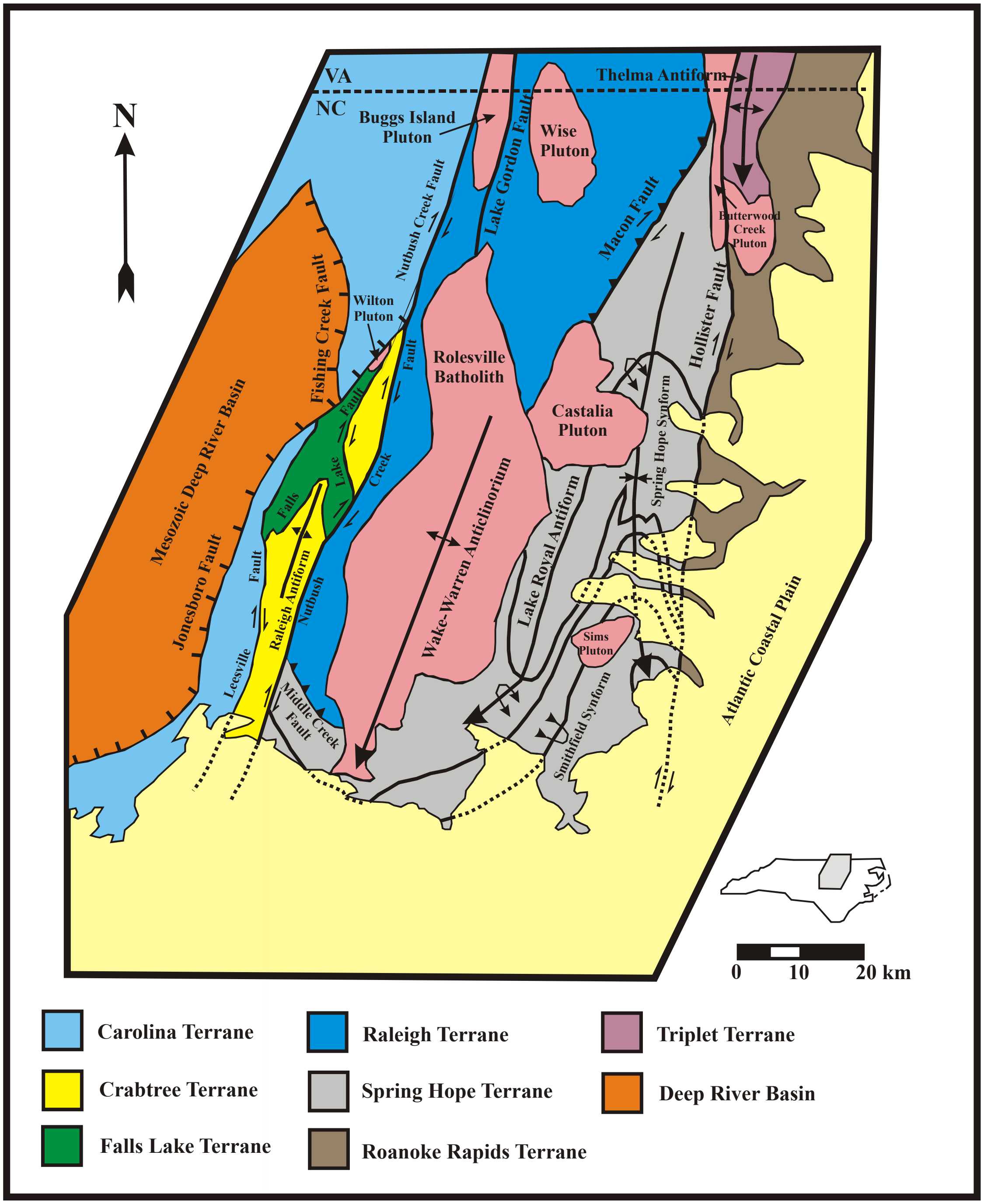


Figure 1: Tectonic terrane map of the Raleigh metamorphic belt in the eastern North Carolina Piedmont. The major plutons are the Rolesville, Castalia, Wise, Sims, Buggs Island, Wilton, and Butterwood Creek. The major folds are the Wake-Warren anticlinorium, the Raleigh, Lake Royal, and Thelma antiforms, and the Smithfield and Spring Hope synforms. The major fault zones are the Jonesboro, Leesville, Falls Lake, Nutbush Creek, Lake Gordon, Macon, Middle Creek and Hollister. Modified from Stoddard and others (1991) and Sacks (1999).

The Carolina terrane, the largest and most intact terrane in the eastern North Carolina Piedmont, occurs east of the Inner Piedmont province and its easternmost portion is the westernmost terrane of the Wake-Warren anticlinorium (Figure 2). On the western flank of the Wake-Warren anticlinorium, the southernmost portion of the Carolina terrane contains the Cary sequence (Parker, 1979; Farrar, 1985a). It is structurally separated from the remainder of the Carolina terrane to the west by the Durham sub-basin (Hibbard and others, 2002) and is structurally higher than the terranes to the east. The Carolina terrane contains lower to upper greenschist facies (chlorite zone) metavolcanic, metavolcaniclastic, and metaplutonic rocks. Many of the lithologies within the Carolina terrane, such as the Turkey Creek Amphibolite, Sycamore Creek Greenstone, and the Big Lake-Raven Rock Schist, preserve relict igneous textures (Blake and others, 2001). The Reedy Creek Metagranodiorite, Beaverdam Metadiorite-Metagabbro (Phelps, 1998), and several smaller bodies represent metamorphosed plutonic rocks. Throughout most of the western flank of the Wake-Warren anticlinorium, a mylonite and phyllonite zone known as the Leesville fault (Figure 2), an Alleghanian dextral fault, forms the eastern boundary of the Carolina terrane (Stoddard and Blake, 1994).

To the east across the Leesville fault, rocks are exposed in the amphibolite facies Falls Lake and Crabtree terranes (Figure 2). Horton and others (1986) interpreted the Falls Lake terrane as an accretionary prism mélange due to its block-in-matrix structure and the exotic nature of the blocks. The Falls Lake terrane displays staurolite-garnet-kyanite zone metamorphism that overprints a mixed assemblage of ultramafic to felsic

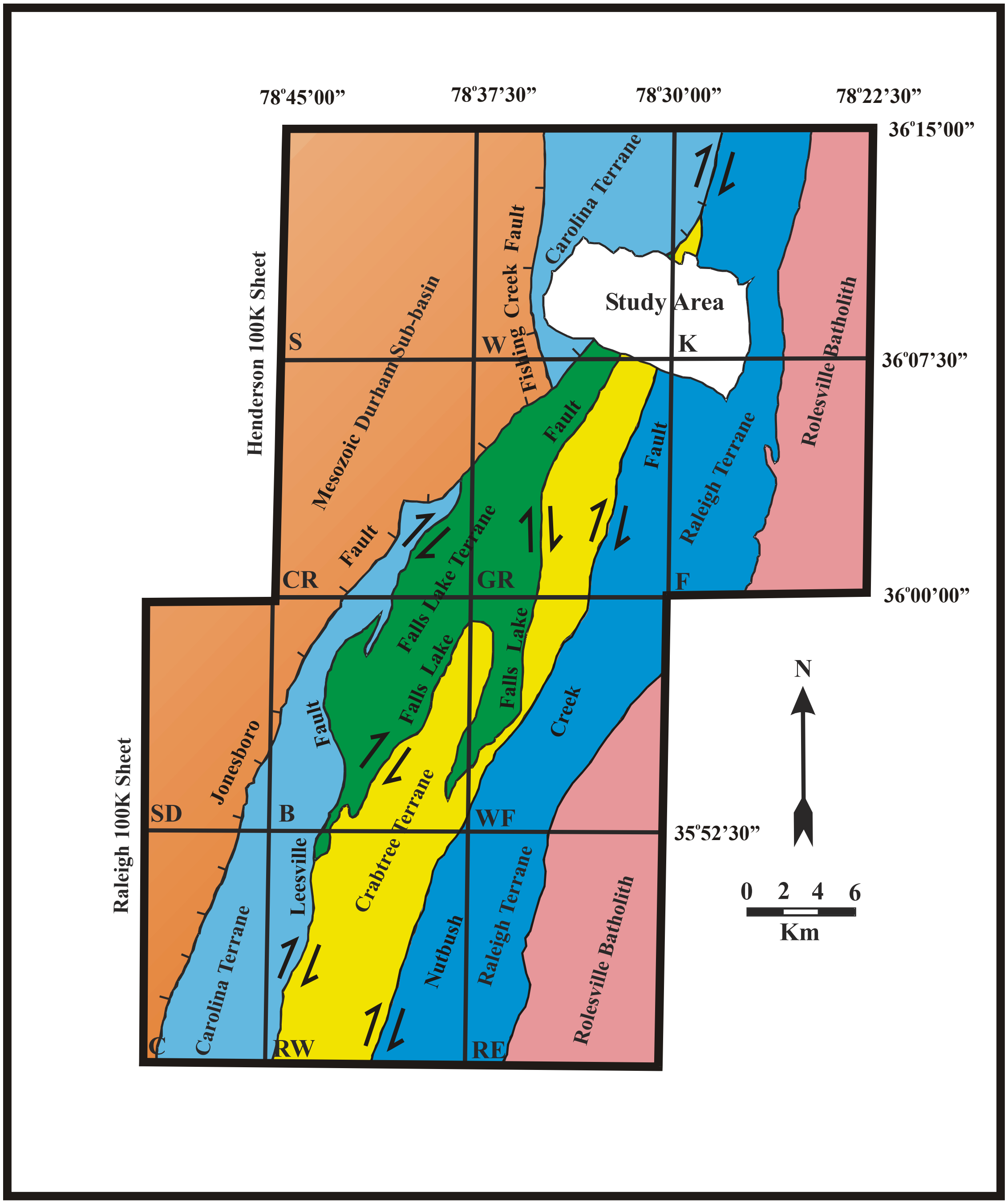


Figure 2: Tectonic map of parts of the Henderson and Raleigh 1:100,000-scale topographic sheets depicting the location of the study area with respect to the Carolina, Falls Lake, Crabtree, and Raleigh terranes, the Rolesville batholith, and the Durham sub-basin of the Triassic Deep River basin. Bounding fault zones are the Jonesboro, Leesville, Falls Lake, and Nutbush Creek. The 7.5-minute-quadrangles represented are Cary (C), Raleigh West (RW), Raleigh East (RE), Southeast Durham (SD), Bayleaf (B), Wake Forest (WF), Creedmoor (CR), Grissom (GR), Franklinton (F), Stem (S), Wilton (W), and Kittrell (K). Modified from Blake (1997).

and pelitic rocks (Moye, 1981; Wylie, 1984; Blake, 1986; Stoddard and others, 1991; Horton and others, 1986; Blake and others, 2002; Clark and others, 2002). The matrix rocks are schist and gneiss and are thought to be metamorphosed mudstone and greywacke. The assemblage of mafic and ultramafic rocks are blocks within the matrix are thought to be a part of a dismembered ophiolite complex (Moye, 1981; Stoddard and others, 1982; Horton and others, 1986).

The contact between the Falls Lake terrane and the Crabtree terrane is the Falls Lake fault zone (Wylie, 1984; Blake, 1986; Stoddard and others, 1994). East of this fault, the Crabtree terrane contains staurolite-garnet-kyanite zone amphibolite facies rocks interpreted as being metasedimentary or metavolcanic in origin. White mica and biotite ± staurolite ± garnet ± kyanite index minerals identify the pelitic schists, while numerous horizons of graphite ± white mica ± garnet ± staurolite ± kyanite schist further attest to the sedimentary origin for parts of the terrane (Parker, 1979; Blake and others, 2001). Some layers contain felsic gneiss with relict plagioclase suggesting dacitic to rhyolitic protoliths (Farrar, 1985a; Stoddard and others, 1991). The Crabtree Creek Gneiss is a metamorphosed pluton that intruded into the Crabtree terrane and has a relict phaneritic texture with relict quartz porphyroclasts (Blake, 1994; Blake and others, 2001).

The Nutbush Creek fault separates the Crabtree terrane from the Raleigh terrane in the southern half of the western flank of the Wake-Warren anticlinorium (Figure 2). The trace of the Nutbush Creek fault (Casadevall, 1977) extends for 200 km from North Carolina into Virginia. The fault is a zone from one to three km wide of lineated mylonite, phyllonite, and gneiss (Druhan and others, 1994). One major elongated body that occurs in the Nutbush Creek fault zone is a granitic orthogneiss, called the Falls

Leucogneiss (Farrar, 1985a). The Falls Leucogneiss is a leucocratic, magnetite-bearing, L-tectonite that occurs between the Crabtree and the Raleigh terranes.

The regional Wake-Warren anticlinorium (Figure 1) exposes the highest-grade rock in the RMB. Within the hinge of the fold, a kyanite-sillimanite zone metamorphism overprints a mixture of igneous and sedimentary protoliths. Metamorphic grade decreases away from the hinge on both limbs. The middle to upper amphibolite facies mineral assemblage of the Raleigh terrane establishes it as the structurally lowest of the RMB (Figure 2). The Raleigh Gneiss is the major rock type within the Raleigh terrane on the western flank. The Raleigh Gneiss is a heterogeneous mixture of interlayered biotite ± hornblende gneiss, chlorite-actinolite rock and a range of intermediate to felsic gneiss (Stoddard and others, 1991; Stoddard and Blake, 1994; Blake and others, 2001). A composite granitoid, the Rolesville batholith, and related graphic and granitic pegmatites intrude the Raleigh Gneiss (Speer, 1994).

The Spring Hope and Roanoke Rapids terranes contain greenschist facies, chlorite-biotite zone felsic and mafic metavolcanic and metavolcaniclastic rocks (Figure 1). The Macon fault zone separates the Spring Hope terrane from the Raleigh terrane. The Spring Hope terrane is structurally higher than the Raleigh terrane and contains the Lake Royal antiform and the Smithfield and Spring Hope synforms (Figure 1). The Hollister fault zone separates the Spring Hope from the Roanoke Rapids terrane. Within the Roanoke Rapids terrane, the Thelma antiform exposes the Littleton Gneiss, an amphibolite facies biotite gneiss that Sacks (1999) terms the Triplet terrane (Figure 1).

A series of late Paleozoic (325 to 265 Ma) granitoid intrusions occur throughout the western flank of the Wake-Warren anticlinorium (Fullagar and Butler, 1979; Sinha and Zietz, 1982; Stoddard and others, 1991). The late Paleozoic intrusions include the Buggs Island, Butterwood Creek, Sims, Wilton, Wise, and Castalia plutons, and the Rolesville batholith (Figure 1). The Rolesville batholith is a composite pluton assembled from differing magmas and intrudes an area of 2000 km^2 in the Raleigh terrane (Speer, 1994).

Mesozoic rifting of the Pangea supercontinent formed the Atlantic Ocean. This event formed graben to half-graben rift basins throughout eastern North America (Olsen, 1991). The Durham sub-basin of the late Triassic Deep River basin is a half-graben that forms the western boundary of the Wake-Warren anticlinorium (Figure 1). The Jonesboro and Fishing Creek faults are brittle normal faults that form the eastern boundary of the Durham basin (Figure 2) and in some areas overprint earlier ductile structures. Several ductile normal faults occur adjacent to the Jonesboro and Fishing Creek faults and may record a Late Permian beginning to the breakup of Pangea. A ductile normal fault within the Coles Branch Phyllite adjacent to the Jonesboro fault yielded a 255 ± 2 Ma $^{40}Ar/^{39}Ar$ muscovite mineral date (Hames and others, 2001; Blake and others, 2001). The Jonesboro fault contains some areas of silicified breccia that follow the trend of the Jonesboro fault while others have an east-west trend (Heller, 1996; Heller and others, 1998; Grimes, 2000). Jurassic diabase dikes associated with rifting intrude the crystalline rock of the Wake-Warren Anticlinorium and sedimentary rocks of the Durham basin.

Blake and others (2001) re-interpreted the development of the eastern Piedmont of North Carolina into three stages (Figure 3). Stage 1 defines the late Proterozoic to middle Paleozoic development of a magmatic island-arc and its accretion to Laurentia.

a.
b.
c.

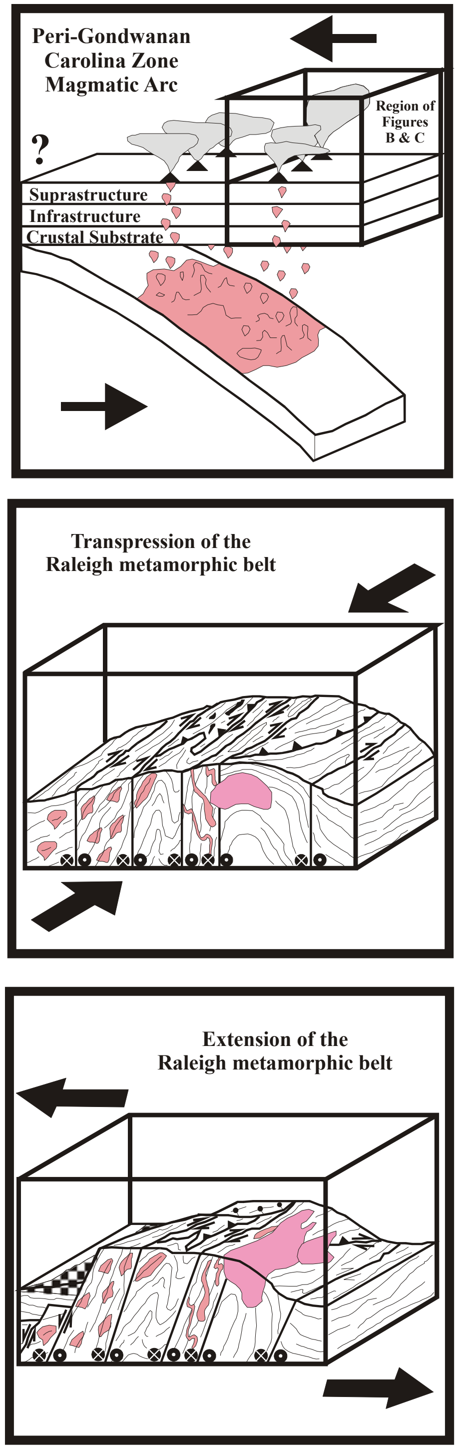


Figure 3: Blake and others (2001) three stage model of the development of the Wake-Warren anticlinorium. a) late Proterozoic to middle Paleozoic development of the peri-Gondwanan volcanic island-arc. b) Alleghanian right-lateral strike-slip and possibly dip-slip faulting, metamorphism, and magmatism. c) Mesozoic breakup of Pangea and the formation of half-graben structures on the western flank of the Wake-Warren anticlinorium.

Stage 2 defines late Paleozoic metamorphism, faulting, and magmatism during the Alleghanian orogeny. Stage 3 defines the late Paleozoic to early Mesozoic development of faults and sedimentary basins during the initial rifting of Pangea and development of the Atlantic Ocean.

Another hypothesis exists for the development of the Wake-Warren anticlinorium. Farrar (1985b) and Farrar and Owens (2001) proposed that the volcanic island-arc was thrust over Grenville-age basement known as the Goochland terrane. In this model, the Wake-Warren anticlinorium produces a structural window in which the lithologic units exposed through Alleghanian folding and faulting are Grenville in age based on a petrographic correlation to the Grenville Goochland terrane in south-central Virginia (Farrar, 1984) (Figure 4). The presence of granulite facies assemblages that include clinopyroxene, orthopyroxene, and sillimanite defines the Goochland terrane (Farrar, 1984; Farrar and Owens, 2001). However, the Lake Gordon and Hylas faults separate the Goochland terrane from the terranes of the western flank of the Wake-Warren anticlinorium (Sacks, 1999; Blake and others, 2001), and a direct correlation between the Goochland terrane and the western flank terranes is tenuous.

Study Area Location and Previous Investigations

The identified terranes and faults in the western flank of the Wake-Warren anticlinorium trend northward into the area of this study defined as the Tar River area. The Tar River area lies within the east-central portion of the Henderson 1:100,000-scale topographic quadrangle. It also lies within parts of the Franklinton, Grissom, Kittrell, and Wilton 1:24,000-scale topographic quadrangles in Franklin and Granville Counties,

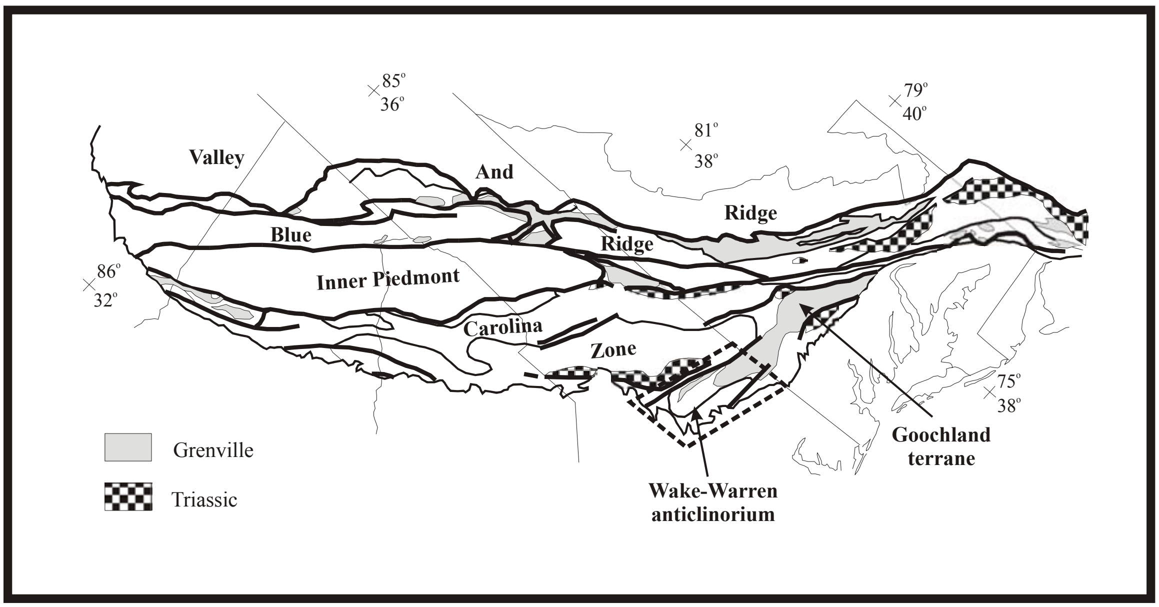


Figure 4: Hypothesis of Farrar (1985b) and Farrar and Owens (2001) for the origin of the Wake-Warren anticlinorium. In this model, the western flank terranes represent an extension of Grenville-age basement in Goochland terrane of southeastern Virginia. Farrar did not recognize the Carolina zone, but it is included for clarity. Modified from Farrar (1985b).

North Carolina (Figure 2). The Tar River area is 45 km northwest of Raleigh and bordered by the Tar River to the north, U.S. Highway 1 to the east, N.C. 56 to the south, and N.C. 96 to the west. The study area encompasses approximately 35 km^2 (21 mi^2) of rural farmland, forestlands, and semi-urbanized areas west of Franklinton, North Carolina.

Carpenter (1970) mapped the Wilton 7.5-minute topographic quadrangle, which included most of the Tar River area. Within the Carolina terrane, Carpenter (1970) mapped a meta-arkose, a metagraywacke, a biotite quartz metadiorite, a metagabbro dike, greenstones, and a suite of metaultramafic rocks. Carpenter (1970) believed that the metaultramafic rocks were intrusive into the various rocks within Carolina terrane. He also mapped a biotite gneiss, a hornblende gneiss, and a quartz monzonite body just east of a siliceous zone (Carpenter, 1970).

Farrar (1980) conducted reconnaissance regional-scale mapping of the eastern Piedmont of North Carolina. Within the Wilton quadrangle, he redefined the biotite quartz metadiorite of Carpenter (1970) and called it the Gibbs Creek Metatonalite (Farrar, 1985).

Druhan (1983) worked east of the zone of siliceous rock (Carpenter, 1970) where he mapped biotite muscovite schist, biotite gneiss, hornblende gneiss, and the Wilton pluton. The mapping of Druhan (1983) concentrated upon the Nutbush Creek fault zone and the Falls Leucogneiss.

Grimes (2000) mapped an area north of the eastern half of Tar River area. He observed a large metaigneous body called the Tabbs Creek complex, which contains a mixture of metagranodiorite, metagabbro, and greenstone (Grimes, 2000). To the east of the Tabbs Creek complex, he mapped a granitic mylonite called the Ruin Creek Gneiss and grouped both of these bodies with the Carolina terrane (Grimes, 2000). Adjacent to the Ruin Creek Gneiss, biotite muscovite schist and gneiss were grouped with the Falls Lake terrane (Grimes, 2000). In the northern portion of his study area, the Ruin Creek Gneiss lies in structural contact with the Falls Leucogneiss.

Grimes (2000) also mapped the Jonesboro fault between the Falls Lake terrane and the Carolina terrane and projected the fault into and terminating within the Falls Leucogneiss. Blake (2001) extended the Jonesboro fault north into the Henderson quadrangle based on brittle structures overprinting ductile fabrics. Grimes (2000) observed the Raleigh Gneiss to the east of the Falls Leucogneiss, as well as a foliated fraction of the Rolesville batholith that he called the Long Creek Gneiss.

Blake and others (2003) mapped within the Carolina terrane north of the Tar River area. They extended the Tabbs Creek complex and the Ruin Creek Gneiss to the south of Grimes (2000) study area. Blake and others (2003) mapped a metagabbro dike and a variety of metadiorite and metagranite. Blake and others (2003) also mapped a metamorphosed biotite tonalite to granodiorite that contained many enclaves of metaultramafic and metamafic rock and small ductile-normal faults. This metamorphosed biotite tonalite to granodiorite is the same body mapped by Carpenter (1970) and Farrar (1980) and hence Blake and others (2003) call it the Gibbs Creek pluton. Several crosscutting diabase dikes were also mapped (Blake and others, 2003).

Blake and others (2002, 2003) mapped the area just to the south of the Tar River area. They found the southern continuation of the metamorphosed Gibbs Creek pluton that was truncated by the Jonesboro fault. To the east of the fault, they mapped a biotite muscovite gneiss, which they grouped into the Falls Lake terrane (Blake and others (2002, 2003). To the east of the Falls Lake terrane, they mapped compositionally interlayered gneiss as part of the Crabtree terrane (Blake and others, 2002, 2003). To the east of the Crabtree terrane, they mapped the Raleigh terrane, and the contact between these two terranes was correlated with the Nutbush Creek fault due to the presence of foliated and lineated rock and the Falls Leucogneiss (Blake and others, 2002, 2003). They also mapped a weakly foliated biotite granitoid within the Raleigh terrane, which they called the Cedar Creek Granite (Blake and others, 2002, 2003).

Statement of the Problem

The western flank of the Wake-Warren Anticlinorium is the product of a complex history of development. The dextral faulting of the eastern Piedmont fault system juxtaposed several terranes with various rock types and metamorphic grades resulting in a metamorphic and structural overprint of the original development of the rocks. A lack of consensus exists for the development of the Wake-Warren anticlinorium, due mainly to confusion about the relationships between terranes as well as the identity of the protoliths within the terranes. Incomplete mapping along the western flank of the Wake-Warren anticlinorium has resulted in the incomplete tracing of faults and terrane boundaries. Finally, the overprinting of brittle structures onto antecedent ductile structures has been recognized as an important piece of the puzzle to unraveling the history of the western flank.

Goals and Objectives

This study categorizes the rock of the Tar River area into terrane terminology used for the western flank of the Wake-Warren anticlinorium through detailed geologic mapping, petrography, laboratory kinematic analysis, and geochemical analysis. The goals for this project are to:

1. Define the lithology and protolith of the lithodemic units in the Tar River area;
2. Locate and describe the position and character of terrane contacts and scale-variable structural geometries and kinematic histories;
3. Examine, evaluate, and define the inter- and intra-terrane metamorphic mineral assemblages;
4. Evaluate the potential for terrane differentiation or affinity using geochemical data from the Tar River area and other locations on the western flank; and
5. Examine and test the various developmental hypotheses for the western flank of the Wake-Warren anticlinorium using the results of this study.

Methodology

Fieldwork was conducted from Fall 1999 through Fall 2000 and consisted of traverse mapping through creeks, across hills, and among roadcuts to provided information for the placement of lithologic and fault contacts. Measurement of foliation, lineation, fold, and fracture orientations was performed using a Brunton compass. USGS topographic 1:24,000-scale maps were used as field and office maps. Both oriented and unoriented hand samples were collected for petrographical and structural analyses of rock types.

Laboratory investigation consisted of preparing thin sections from these hand samples in the UNCW Earth Sciences Petrology Preparation Laboratory and performing a detailed petrographic and kinematic study of the rock types. Samples for geochemical analysis were also prepared in the UNCW Earth Science Petrology Preparation Laboratory and sent to XRAL laboratories (Don Mills, Ontario) for analysis of whole-rock major and trace elements. Mineralogic data was gathered from the thin sections using an Olympus 8061 microscope. Structural data was plotted on stereonets using the Allmendinger Stereonet 4.6 program on a Macintosh computer. Graphs and figures were produced using Corel Draw 10, Adobe Illustrator 9, and IgPet 2000 programs. The North Carolina Geological Survey produced a finalized digitized geologic map and a station location map.

LITHOLOGIC UNITS

Introduction

The lithologic units of the Tar River area (Figure 5) represent a mixture of late Proterozoic to Cambrian metaplutonic, plutonic, and possibly metasedimentary rocks. A late Paleozoic granitic pluton intruded these metamorphic rocks in the central portion of the Tar River area, and pegmatitic granite and diabase dikes intrude locally. A ridge of silicified breccia extends north to south across the Tar River area and divides it into two unequal halves. Quaternary alluvium overlies the metamorphic and igneous rocks along creeks and the Tar River where the topography is low. The metamorphic rocks of the Tar River area have been correlated with the terrane assignment criteria of Horton and others (1989) and Stoddard and others (1991) for the western flank of the Wake-Warren anticlinorium. Lithologic units of the Tar River area are described in relative age relationship from youngest to oldest and structurally highest to lowest.

Sedimentary Unit

Quaternary Alluvium (Qal)

Quaternary alluvium occurs along the Tar River and Ford, Middle, and Taylors Creeks as floodplain, natural levee, point bar, and stream deposits. This material is an unconsolidated, poorly stratified and poorly- to well-sorted, tan to light gray sand and gravel that contains local clay and silt horizons. In some localities, gravel includes boulder-sized clasts of metaigneous rock, granite, and pegmatite rock.

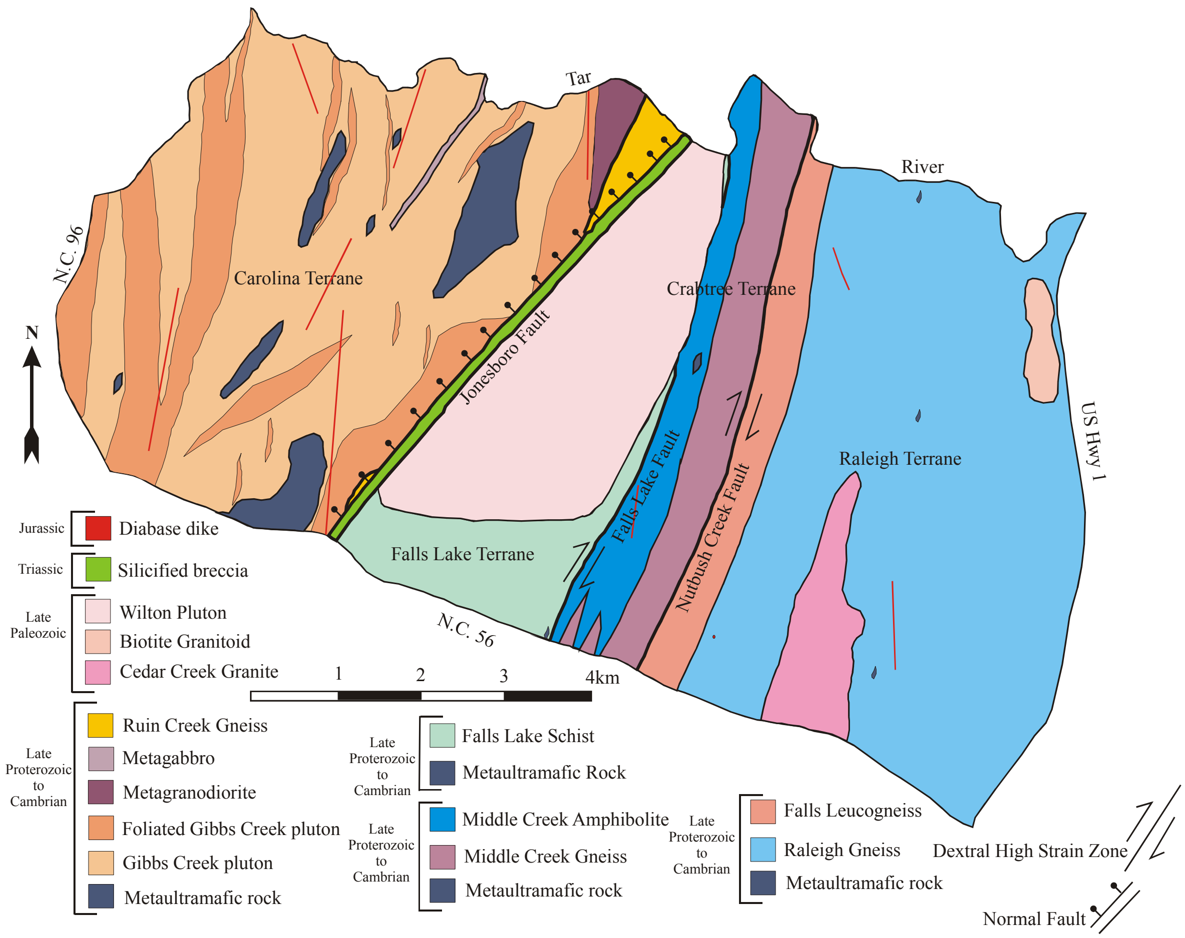


Figure 5: Geologic map of the Tar River area.

Intrusive Units

Diabase Dikes (Jd)

Diabase intrusions are distributed throughout the area as approximately 2 m wide dikes having two distinct orientation trends. One group trends northwest-southeast while the other trends north-south (Figure 5). The discontinuous linear trend of boulder fields and creek outcrops (Figure 6a) was used to map the extent of the diabase dikes. Diabase boulders exhibit spheroidal weathering and are usually dark brown to black in outcrop (Figure 6b). In hand sample, the dikes are dark brown to bluish-black, fine- to medium-grained olivine-bearing diabase. The diabase texture ranges between a basalt and a gabbro, and can occasionally be more gabbroic.

Petrographic Relationships

In thin section, the diabase dikes display an ophitic to subophitic texture (Figure 7a). The primary minerals are plagioclase (An_{35-40}), clinopyroxene, orthopyroxene, and olivine. Plagioclase occurs in tabular laths and is idiomorphic to xenomorphic. Clinopyroxene and orthopyroxene crystals are xenomorphic to subidiomorphic. The subidiomorphic olivine is slightly larger than the plagioclase, clinopyroxene, and the orthopyroxene groundmass. Opaque accessory minerals are magnetite or ilmenite.

The more gabbroic dikes display ophitic to subophitic texture (Figure 7b). Plagioclase crystals (An_{35-40}) contain radiate intergrowth of augite and enstatite. Granophyric texture occurs around some of the plagioclase crystals. Accessory minerals are rutile and opaque minerals.

a.

b.

Figure 6: a) Typical outcrops of diabase boulders with Ben Grosser and author for scale. b) A cobble of the diabase displaying spheroidal weathering, which is common on diabase cobbles. The scale bar is 15.24 cm long.

a.

b.

Figure 7: a) Photomicrograph of a diabase dike is the typical diabase texture. b) A gabbroic texture locally developed in some dikes. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm for both a and b.

Correlation and Age

The diabase correlates to a regional swarm of dikes that intrude the eastern Piedmont from Alabama to Virginia and have intruded all terranes within the Tar River area (Parker, 1979; Ragland, 1991). On the western flank of the Wake-Warren anticlinorium, the dikes intrude Alleghanian intrusive bodies and Triassic sedimentary rock as well, but have not intruded Cretaceous sedimentary rocks (Parker, 1979; Ragland, 1991). Based on these contact relationships, the diabase dikes are determined to be Jurassic in age (de Boer, 1967).

Pegmatite dikes and sills (Ppd)

Pegmatite dikes and sills are primarily found in the higher-grade metamorphic facies rocks east of the silicified breccia ridge in proximity to the Wilton pluton and the Rolesville batholith. Some small, cm-wide veins occur within the foliated rock just west of the silicified ridge, while some of the larger pegmatites dikes are found within the Middle Creek Gneiss and the Raleigh Gneiss. The pegmatite dikes are elongate, having a NE-SW trend and range in size from mm to m. In hand sample, the pegmatitic granite to graphic pegmatitic granite dikes are pink to grayish-white in color, very coarse grained, and nonfoliated.

Petrographic Relationships

Primary minerals include microcline, plagioclase, quartz, muscovite, biotite, and garnet. In the graphic pegmatite, quartz is intergrown with microcline and plagioclase. The pegmatite dikes display a granitic texture.

Correlation and Age

Based on mineralogy and proximity, these pegmatite dikes are probably related to the Rolesville batholith and satellite bodies located within and just east of the field area. Coler and others (1997) estimated the Rolesville batholith as having an age of approximately 300 Ma. Schneider and Samson (2001) conducted U-Pb zircon geochronology on three of the phases of the batholith and reported a 298 Ma date for the pulse of magmatism.

Wilton pluton (Pwp)

The Wilton pluton is located in the center of the Tar River area and is about 5 km long and 2.5 km wide and encompasses about 10% of the area. The Wilton pluton weathers into large boulders and pavement outcrops that are found on hilltops and along creeks (Figure 8a). The best exposure is found in an abandoned quarry southeast of Mayfield Mountain (Figure 5; Plate 1). The Wilton pluton intrudes into the biotite white mica schist and gneiss of the Falls Lake terrane and the Middle Creek Gneiss of the Crabtree terrane. The silicified ridge truncates the pluton on its west side. The Wilton pluton is a biotite granite that appears leucocratic (CI<15) and grayish orange to pink in color, and is medium to coarse grained (Figure 8b). The Wilton pluton is nonfoliated, but along the eastern boundary there is a weak biotite mineral aggregate and felsic shape lineation.

a.

b.

Figure 8: a) A field photograph of a pavement outcrop of the Wilton pluton, which is common within the Tar River area. Ben Grosser and author for scale. b) Close-up of an outcrop of the Wilton pluton displaying a typical orange to pink color. Scale bar is 15.24 cm long.

Petrographic Relationships

The Wilton pluton displays a granitic texture at the mesoscale and microscale. Primary minerals are quartz, microcline, plagioclase (An_{10-15}), and biotite. The minerals are inequigranular and have a bimodal grain size distribution. Microcline and quartz crystals are the larger than the plagioclase and biotite crystals. Microcline displays microperthitic texture, and along with plagioclase, displays sericitization. Quartz exhibits undulatory extinction. Accessory minerals include opaque minerals. Secondary chlorite occurs as the result of a reaction replacement of biotite.

Correlation and Age

The Wilton pluton trends to the north of the Tar River area, but no outcrops have been found or mapped. The Wilton pluton is part of a group of Carboniferous to Permian age Alleghanian plutons that intrude the eastern Piedmont of North and South Carolina (McSween, 1991). The Wilton Pluton yields a 285 ± 10 Ma Rb-Sr whole-rock date (Fullagar and Butler, 1979).

Granitic Gneiss (Pcg, Pbg)

Two granitic gneiss bodies intrude into the eastern portion of the Raleigh terrane in the Tar River area. One of these small bodies called the Cedar Creek granite (Pcg) (Horton, 1985; Blake and others, 2002), crops out between Taylors Creek and County Road 1203, just north of NC 56 (Figure 5; Plate 1). The second is an elongate biotite granitoid body (Pbg) just south of the Tar River and between Taylors Creek and US 1 (Figure 5; Plate 1). In outcrop and hand sample, these two granitic gneiss bodies are a medium to coarse grained, grayish-white to pink, nonfoliated to weakly-foliated, biotite and white-mica granite (Figure 9).

Petrographic Relationships

At the mesoscale, the primary minerals are microcline, biotite, quartz, and plagioclase. Accessory minerals are opaque minerals, including magnetite and pyrite. These bodies have a granitic texture and a weak alignment of biotite plates. The quartz crystals have an undulatory extinction.

Correlation and Age

Grimes (2000) mapped the Long Creek Gneiss to the north and interpreted it to be a weakly foliated facies of the Rolesville batholith. Horton (1985) and Blake and others (2002) mapped a weakly foliated granite south of the Tar River area, which is a continuation of the Long Mill Gneiss that occurs between Taylors Creek and County Road 1203. These bodies are probably isolated satellite facies to the Rolesville batholith in which Schneider and Samson (2001) obtained a 298 Ma U-Pb zircon date on the main magmatism.

Fault Breccia

Silicified Breccia (Trsb)

Silicified breccia occurs in a 50 m wide zone that forms several prominent, linear ridges within the Tar River area (Figure 5; Plate 1). This zone extends across the central

Figure 9: Outcrop picture of a typical appearance of the Cedar Creek granite just south of NC 56. Scale bar is 15.24 cm long.

portion of the Tar River area and trends N40E. The silicified ridges along this trend occur at Mayfield Mountain, a ridge just northeast of Mayfield Mountain, and a ridge along the Tar River (Plate 1). The silicified breccia forms the peaks of the ridges and along their lower slopes, brecciated pieces of greenstone and Gibbs Creek pluton cemented with silica are exposed.

Within the silicified breccia zone, small pieces of breccia ranging from gravel to cobble-size are observed (Figure 10a). Massive white to gray outcrops of silicified breccia cap the ridges (Figure 10b). In hand sample, the silicified breccia is a light gray to white rock that has been multiply brecciated and some hand samples contain milky quartz fracture fill.

Petrographic Relationships

At the microscale, thin sections from the peaks of the major ridges display inequigranular texture. Large idiomorphic to subidiomorphic quartz crystals along with smaller brecciated and microcrystalline quartz infill the space between the larger crystals (Figure 11a). Quartz does not exhibit undulatory extinction. The brecciated greenstone from the valleys reveals microcrystalline quartz fracture fill and vuggy quartz crystals that form in open spaces between breccia pieces (Figure 11b).

Correlation and Age

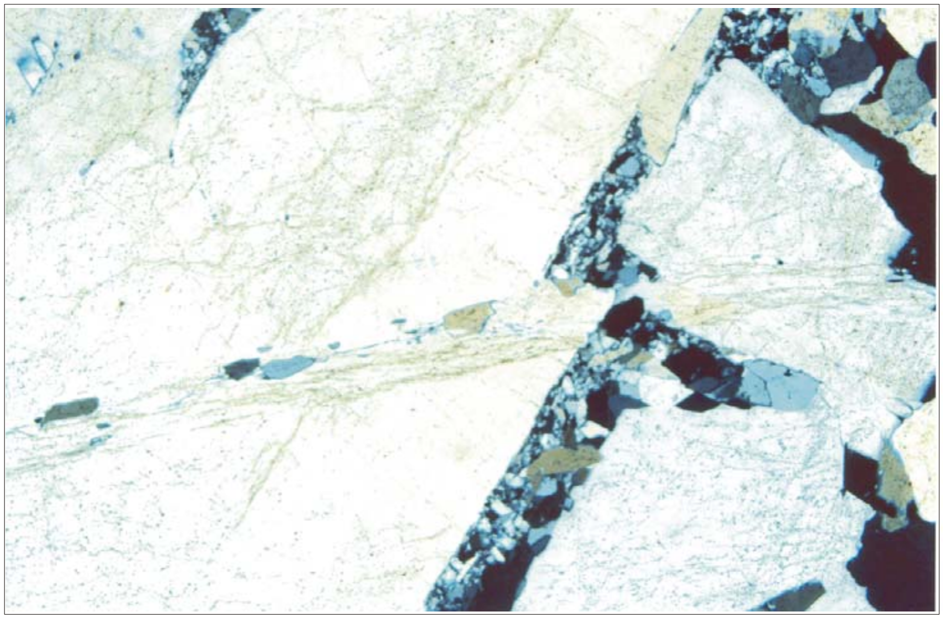
The silicified ridge is traced to the north and correlates to Little Egypt Mountain where Grimes (2000) mapped silicified breccia along the ridge. Blake and others (2002) also found silicified breccia along prominent ridges to the south of the Tar River area and

a.

b.

Figure 10: a) Hand samples of the silicified breccia displaying fractures. Rock hammer (27 cm long) for scale. b) A typical boulder outcrop of the silicified breccia. These boulders cap the ridges in the Tar River area. Brian O Shaunghessy and MacIntyre for scale.

a.



b.

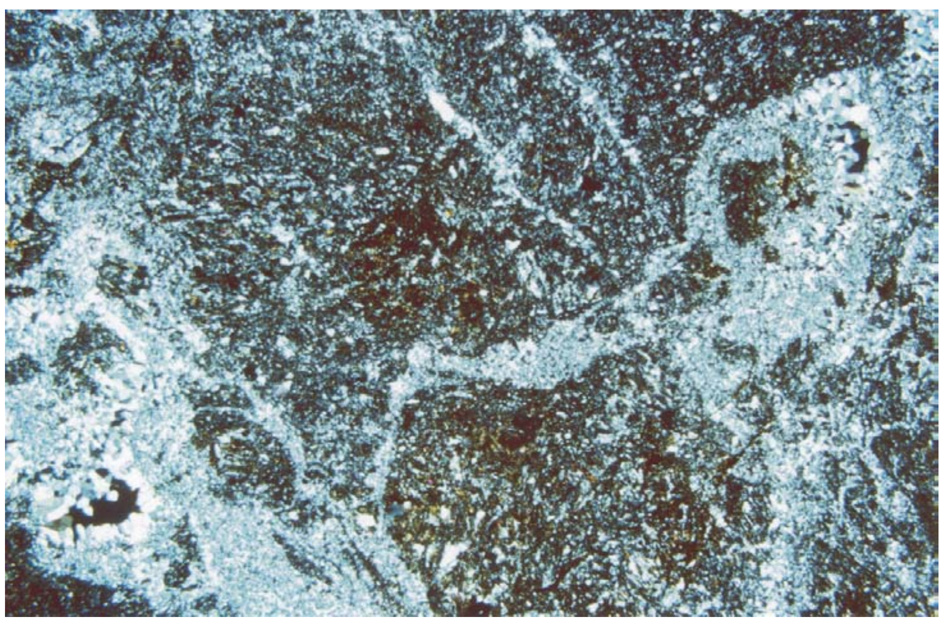


Figure 11: a) Photomicrograph of silicified breccia displaying multiple brecciation from a boulder at the cap of a ridge. b) A brecciated greenstone from the silicified ridge. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm for both a and b.

into the Creedmoor quadrangle. The silicified ridge marks a fault trend and will be discussed further in the STRUCTURE CHAPTER. This fault is related to Mesozoic rifting and is probably late Triassic in age.

Carolina Terrane

Lithologic units assigned to the Carolina terrane comprise approximately 40% of the field area (Figure 5; Plate 1). Units within this terrane range in composition from ultramafic to felsic. The main lithologic unit within the Carolina terrane is the Gibbs Creek pluton, a metagranodiorite to metatonalite body. It contains four different types of enclaves, Type 1 greenstone, Type 2 amphibolite, Type 3 metaultramafic rocks, and Type 4 foliated metagranitoid. The Gibbs Creek pluton is in contact with a foliated metagranodiorite and the Ruin Creek Gneiss to the east and is truncated by the silicified ridge. In addition, a metagabbro dike intrudes into the Gibbs Creek pluton. To the west, the Carolina terrane rocks continue out of the field area where they terminate against the Fishing Creek fault that bounds the northeast Durham Basin.

Metagabbro (€Zmg)

The metagabbro dike that intrudes the Gibbs Creek pluton is approximately 100-m wide and 1.2 km long. It outcrops in a tributary to the Tar River, on hilltops, and along the Tar River, trending N50E northward out of the Tar River area. Outcrops of the metagabbro form large gray to black boulders, and float rock has a blue green appearance (Figure 12a). Hand samples appear bluish gray to black, medium-grained, and massive (Figure 12b) with relict phenocrysts of plagioclase.

a.

b.

Figure 12: a) Large dark boulders in a typical outcrop of the metagabbro. The author for scale. b) Hand sample photograph of the metagabbro showing a bluish green appearance. The scale bar is 15.24 cm long.

Petrographic Relationships

At the microscale, the metagabbro has an ophitic to subophitic texture. Relict primary minerals are plagioclase (An_{40}), clinopyroxene, and orthopyroxene. Hornblende, actinolite, chlorite, and epidote mineralization overprints the primary minerals. Most pyroxene crystals are xenomorphic to hypidiomorphic and have undergone uralitization to actinolite prisms. Some chlorite has formed on the edges of the relict pyroxene. In some of the more altered metagabbro rock, the plagioclase crystals have been saussuritized. Opaque minerals (pyrite and magnetite) occur as accessory minerals.

Correlation and Age

The metagabbro extends to the north of the Tar River area and is equivalent to the metagabbro body mapped by Carpenter (1970) and Blake and others (2003). Based upon contact relationships, the metagabbro is a dike and intrudes into the Carolina terrane and crosscuts older units, specifically the Gibbs Creek pluton. A precise age is uncertain, but based upon crosscutting relationships the metagabbro is possibly one of the younger late Proterozoic to Cambrian units in the easternmost Carolina terrane within the Tar River area.

Ruin Creek Gneiss (ЄZrc)

The Ruin Creek Gneiss crops out along the west side of the silicified ridge in two distinct areas: 1) just south of the Tar River and 2) just southwest of Mayfield Mountain (Figure 5; Plate 1). The Ruin Creek Gneiss is in contact with the metagranodiorite to the west and is truncated by the silicified ridge to the east. Hand samples of the Ruin Creek

Gneiss are reddish-orange to green and fine- to medium-grained, well foliated and subhorizontally lineated and have a penetrative mylonitic fabric. Outcrops south of the Tar River are more fine-grained than outcrops near Mayfield Mountain, which contain more chlorite and larger K-feldspar porphyroclasts.

Petrographic Relationships

The primary minerals for the Ruin Creek Gneiss are microcline, quartz, biotite, white mica, and plagioclase ($An_{\sim 20}$). Microcline and plagioclase have undergone sericitization and display perthitic texture. Some epidote occurs within the feldspar crystals and there is reaction replacement of biotite to chlorite. The Ruin Creek Gneiss displays a mylonitic microstructure and contains a strong foliation. Recrystallized quartz ribbons and the alignment of white mica and chlorite define a gneissic layering. Other evidence of mylonitization are sigma-type microcline porphyroclasts having white mica, chlorite, and recrystallized quartz tails. Accessory minerals are opaque minerals such as pyrite.

Correlation and Age

The Ruin Creek Gneiss has been mapped north of the Tar River area (Grimes, 2000) and into the Henderson quadrangle (Blake, 2001; Blake and others, 2003). The age of the Ruin Creek Gneiss has not yet been determined, but may be late Proterozoic to late Paleozoic. Trace element discrimination diagrams suggest a correlation with late Paleozoic, Alleghanian plutons (Blake and Stoddard, 2004).

Foliated Metagranodiorite (ЄZgdf)

A foliated metagranodiorite unit outcrops in the northeast portion of the Carolina terrane and lies in contact between the Gibbs Creek pluton to the west and the Ruin Creek Gneiss to the east (Figure 5; Plate 1). The silicified ridge truncates the southern end of this unit. In outcrop, this unit is light to dark grayish green, fine to coarse grained, and contains a strong protomylonite to mylonite foliation.

Petrographic Relationships

In thin section, the primary minerals are quartz, plagioclase, K-feldspar, white mica, and biotite. Secondary minerals are chlorite and epidote. Chlorite has replaced the biotite and is the dominate mineral. Chlorite and white mica are aligned with quartz and plagioclase porphyroclasts. Opaque minerals are accessory such as pyrite.

Correlation and Age

This unit has been mapped just north of the Tar River area (Blake and others, 2003; Pesicek, 2003). The contact of the metagranodiorite with respect to the Gibbs Creek pluton and the Ruin Creek Gneiss is poorly exposed, but based upon its textures, it was most likely an intrusive unit within the Caroline terrane and late Proterozoic to Cambrian in age.

Gibbs Creek pluton (ЄZgc)

The Gibbs Creek pluton comprises most of the Carolina terrane rocks within the Tar River area. The best exposure occurs along the Tar River where the relief is steep and outcrops form ledges and large boulders. Additional exposure occurs in many tributary creeks and hillsides where the pluton weathers into large boulders. Some hillside outcrops weather to a rusty-red clay + quartz + white mica rock. The outcrops of the Gibbs Creek pluton vary in appearance depending upon the weathering. In hand sample, the Gibbs Creek pluton is gray-green, fine to medium grained, and unfoliated. The pluton is a metamorphosed biotite tonalite to granodiorite containing relict hornblende, biotite, plagioclase, K-feldspar, quartz, and metamorphic epidote, chlorite, white mica, and opaque minerals. The Gibbs Creek pluton contains four varieties of enclaves. These enclaves are separated in four types and are randomly distributed throughout the Gibbs Creek pluton.

Petrographic Relationships

In thin section, the Gibbs Creek pluton displays a granitic texture (Figure 13). Primary minerals in the Gibbs Creek pluton are plagioclase (An_{35-40}), quartz, biotite, and minor microcline. Plagioclase is variably sericitized and/or sausseritized, but relict crystals still retain a subidiomorphic to xenomorphic form. The sericite and epidote occurs within the plagioclase. Metamorphic chlorite has replaced the igneous biotite. The quartz has undulose extinction and is primary. Carpenter (1970) identified the accessory opaque minerals within the rock as magnetite. Other accessory minerals are rutile and tourmaline.

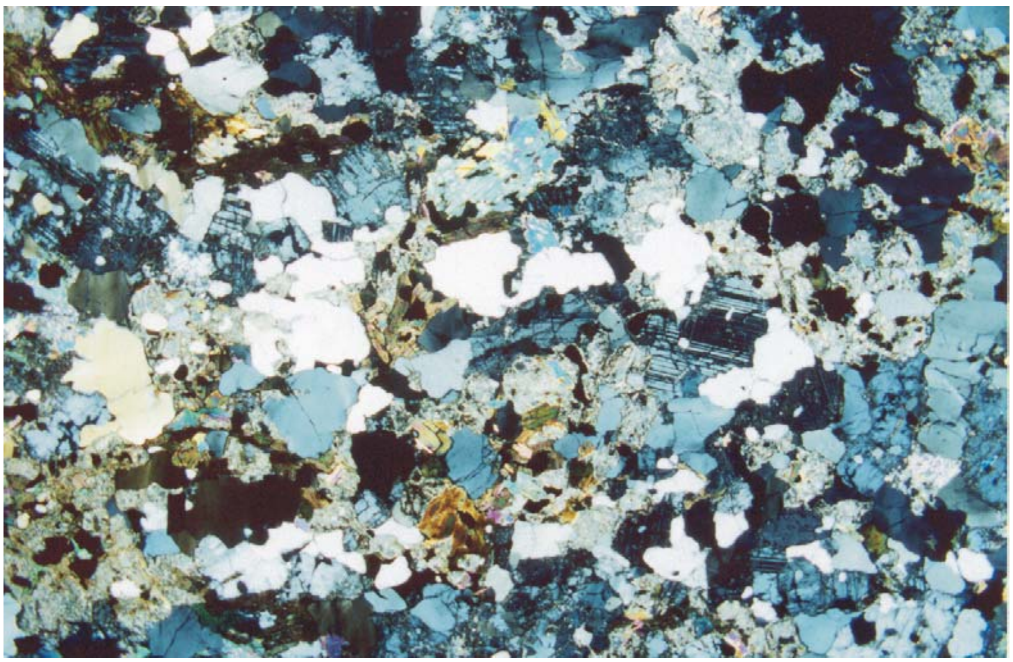


Figure 13: Photomicrograph of the Gibbs Creek pluton. Feldspars display sericitization and sausseritization. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm.

Correlation and Age

Carpenter (1970) first mapped the Gibbs Creek pluton as a biotite quartz diorite. Farrar (1985a) later changed the biotite quartz diorite classification to the Gibbs Creek metatonalite. Blake and others (2002, 2003) mapped the Gibbs Creek metatonalite to the north and south of the Tar River area and informally renamed it the Gibbs Creek pluton, suggesting it may have some minor granodiorite facies. An exact age has not been determined for the Gibbs Creek pluton, but it is reported as being late Precambrian to Cambrian in age (Stoddard and others, 1991).

Enclaves (€Zu)

Four types of metamorphosed enclaves are randomly distributed throughout the Gibbs Creek pluton. Often the enclaves are angular and blocky to rounded and folded, and have a random orientation within the Gibbs Creek pluton.

Type 1 enclaves consist of greenstone that range in size from mm to m in diameter. The best exposure of the greenstone enclaves occurs within a km west of the county Road 1622 bridge along the Tar River. The greenstone enclaves are more susceptible to chemical weathering and leave depressions or voids within the rock. The greenstone enclaves appear light green to dark green in color and are fine to medium grained and rounded to angular, and locally folded.

Type 2 enclaves are amphibolite that range in size from mm to m in diameter. The best exposure of the amphibolite enclaves also occurs within a km west of the County Road 1622 bridge on the Tar River. The amphibolite appears light to dark green, layered, well foliated, angular to blocky, and sometimes may be folded.

Type 3 enclaves are a variety of metaultramafic rocks. These differ from the other enclaves as the majority of the metaultramafic enclaves are mappable. Two large, and several smaller, metaultramafic bodies outcrop with in the Tar River area. One large metaultramafic body outcrops in the southern part of the Tar River area on Ford Creek and the other outcrops to the north near the Tar River.

These enclaves are randomly distributed throughout the extent of the pluton and are much larger than the greenstone enclaves, generally several m in width and length. The metaultramafic rock enclaves within the Tar River are talc schist, serpentinite, and actinolite-bearing serpentinite bodies. These metaultramafic types may occur independently or as a lithologic assemblage. The smaller enclaves are mainly talc schist while the larger enclaves contain serpentinite and talc schist. Poor exposure of these enclaves makes the contact relationships difficult to interpret, although the Ford Creek ultramafic body contains a ring of talc schist surrounding serpentinite rock. Carpenter (1970) noticed that the talc-rich rocks are more abundant within the margins of the bodies than near the center. In hand sample, the metaultramafic rock enclaves appear dark gray to green and fine to medium grained. The enclaves exhibit massive to well foliated textures.

Type 4 enclaves are foliated metagranitoids. These bodies range in size from mm to m in diameter. The best exposure of the foliated metagranitoid enclaves is just west of the County Road 1622 bridge on the Tar River. These enclaves appear to be foliated equivalents of the Gibbs Creek pluton.

Petrographic Relationships

At the mesoscale, Type 1 greenstone enclaves have a granoblastic texture. The primary minerals are plagioclase and actinolite and thin section examination reveals heavy saussuritization of the plagioclase. Secondary epidote occurs within and between plagioclase crystals, while the actinolite displays reaction replacement to chlorite.

Type 2 amphibolite enclaves contain alternating layers of plagioclase and hornblende. The plagioclase layers are generally thinner than the hornblende layers. The plagioclase displays reaction replacement to epidote and sericite, which gives the plagioclase layers a light green appearance in hand sample. The hornblende displays reaction replacement to chlorite and gives a darker appearance.

Type 3 metaultramafic enclaves are actinolite-bearing serpentinite, talc schist, and serpentinite. The talc schist is mainly fine-grained talc, having a massive texture. At the microscale, the serpentinite contains fine-grained serpentine and minor amounts of talc and chlorite. Some samples contain idioblastic to subidioblastic crystals of actinolite. All of the metaultramafic rocks contain accessory opaque minerals such as ilmenite.

The Type 4 enclaves have a similar mineralogy at the microscale with the Gibbs Creek pluton, but are foliated. The primary minerals are plagioclase (An_{35-40}), quartz, biotite, and microcline. Plagioclase is variably sericitized and/or sausseritized, but relict crystals still retain an idiomorphic to xenomorphic form. The sericite and epidote occurs as microlites within the plagioclase. Biotite displays reaction replacement to chlorite. The quartz has undulose extinction and is primary. Accessory opaque minerals are most likely magnetite. Other accessory minerals are rutile and toumaline.

Correlation and Age

All four types of enclaves are found within the Gibbs Creek pluton to the north Blake and others, 2003; Pesicek, 2003) and the south of the Tar River area (Blake and others, 2002). The origin and correlation of the greenstone, amphibolite, metaultramafic, and foliated granodiorite enclaves is uncertain. Hypotheses for the origin and correlation of these enclaves will be discussed further in the GEOCHEMISTRY and the DISCUSSION CHAPTER. Based on the principle of inclusions, all of the enclaves are older than the Gibbs Creek pluton.

Falls Lake Terrane

The Falls Lake terrane is composed of the Falls Lake Schist and a metaultramafic body. The silicified ridge truncates the Falls Lake to the west and it is in contact with the Middle Creek Gneiss of the Crabtree terrane to the east (Figure 5; Plate 1). The Wilton pluton intrudes into the Falls Lake terrane along its northern boundary. The Falls Lake terrane comprises about 10% of the Tar River area.

Falls Lake Schist (ЄZfs)

The Falls Lake Schist outcrops in the middle of the field area and lies east of the silicified ridge (Figure 5; Plate 1). The eastern boundary is in contact with the Middle Creek Gneiss, but due to poor outcrop exposure there is a poor relationship between the two units. The lack of exposure is due to weathering and the intrusion of the Wilton pluton that truncates the schist to its north. There is a variation in the amount of mica and quartz in some outcrops that results in a variation of the texture (gneissic to schistose) of the rock. This unit appears as an orangish-gray, fine to medium grained, well foliated and lineated, and thinly layered, garnet-bearing, biotite white mica schist and gneiss.

Petrographic Relationships

Primary minerals for the more biotite-rich samples, are biotite, quartz, plagioclase, and garnet. Accessory minerals are apatite and opaque minerals. Biotite displays reaction replacement to chlorite. Rectangular opaque minerals contain a deep reddish hue, which may indicate pyrite alteration to limonite. The white mica-rich samples contains white mica, quartz, plagioclase, and garnet. Foliation varies from schistose to a thin gneissic layering of quartz and biotite and white mica. The garnet porphryoblasts are poikiloblastic with quartz inclusions that do not display undulatory extinction.

Correlation and Age

Carpenter (1970), Druhan (1984), and Blake and others (2002) mapped the Falls Lake Schist to the south of the Tar River area. To the south, zircon U/Pb dates from a white mica-biotite-quartz-feldspar schist in the Falls Lake terrane yielded a late Proterozoic 590 Ma date (Goldberg, 1994).

Talc chlorite actinolite rock (ЄZfu)

A metaultramafic rock occurs just north of NC 56 within the Falls Lake terrane near the contact of the Crabtree terrane. Total extent of the outcrop and other bodies of metaultramafic rock is difficult to determine due because of poor exposure. Samples of metaultramafic rocks primarily litter the tops of hills as float. The metaultramafic rock is a talc chlorite actinolite rock and appears light to dark green and is fine- to medium-grained in outcrop.

Petrographic Relationships

The metaultramafic rock contains talc, actinolite, and chlorite in varying amounts. Thin sections contain idioblastic to subidioblastic prisms of actinolite with lesser amounts of talc and chlorite plates. Accessory minerals are opaque minerals, such as ilmenite, magnetite, and chromite.

Correlation and Age

Other metaultramafic rock in the Falls Lake terrane have been mapped to the south (Moye, 1981; Wylie, 1986; Blake, 1986; Horton and others, 1986; Blake and others 2002). These bodies are hornblendite, actinolite-clinozoisite rock, serpentinite and talc, talc-actinolite, talc-tremolite, and actinolite-chlorite schist. Moye (1981) suggested that the bodies with the Falls Lake terrane are part of a dismembered ophiolite complex and based on the principle of inclusions are older than the Falls Lake terrane matrix.

Crabtree Terrane

The Crabtree terrane lies in the central portion of the Tar River area and comprises about 15% of the area. The Crabtree terrane contains the Middle Creek Gneiss, which includes a felsic to intermediate to mafic gneiss along with a metaultramafic layer. A prominent amphibolite body, the Middle Creek Amphibolite, occurs along the western boundary. The Crabtree terrane is in contact with the Falls Lake terrane to the west across the Falls Lake fault zone and the Falls Leucogneiss to the east across the Nutbush Creek fault zone (Figure 5; Plate 1). The Wilton pluton intrudes into the Crabtree terrane along its northwest boundary.

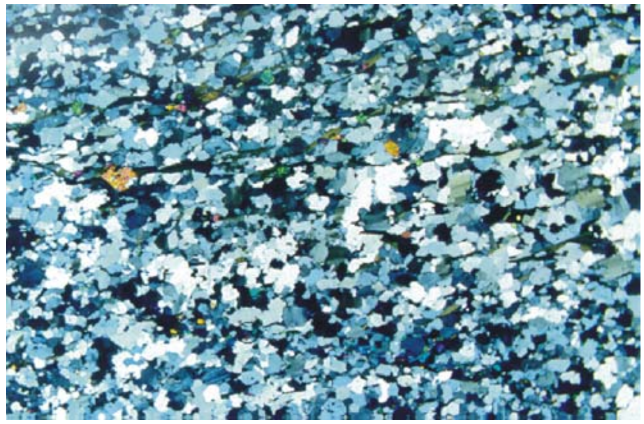
Middle Creek Gneiss (Єzmcg)

The Middle Creek Gneiss trends approximately N15E to N20E and comprises most of the Crabtree terrane (Figure 5; Plate 1). Exposure of the Middle Creek Gneiss is found along creeks, road cuts, and the Tar River. The Middle Creek Gneiss is a thin layered (mm to m) gneiss ranging from felsic, intermediate, to mafic in composition. The Middle Creek Gneiss is a light gray to black, fine- to medium-grained, well-foliated and lineated, biotite white mica gneiss, biotite to biotite hornblende gneiss, and amphibolite.

Petrographic Relationships

All units of the Middle Creek Gneiss contain a gneissic foliation. Primary minerals for this layered gneiss are biotite, hornblende, white mica, plagioclase, and microcline. The felsic gneiss contains white mica, quartz, and plagioclase and small amounts of biotite, while the intermediate samples contain more biotite (Figure 14a, b). The more mafic samples are primarily hornblende and plagioclase (Figure 14c). Biotite, hornblende, and white mica are interlayered between quartz, plagioclase, and microcline. All minerals are dynamically recrystallized. The Middle Creek Gneiss contains a mineral aggregate lineation. Plagioclase and microcline have experienced a varying degree of sericitization. Secondary epidote occurs alone or within feldspars, and there is topotacitic

a.



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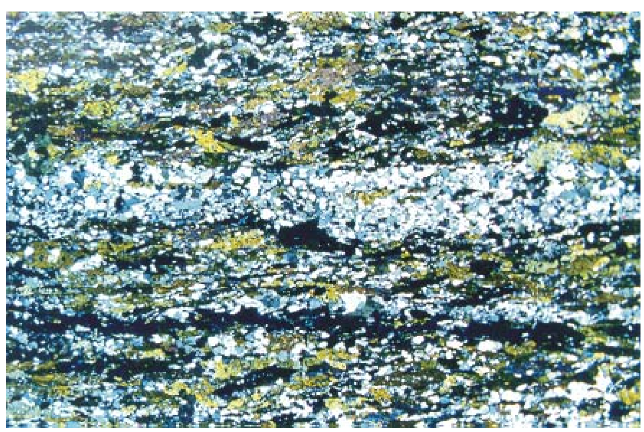


Figure 14: a) Photomicrograph of a felsic gneiss within the Middle Creek Gneiss. b) Photomicrograph of an intermediate gneiss from the Middle Creek Gneiss. c) Photomicrograph of a mafic gneiss from the Middle Creek Gneiss. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm for a, b, and c.

transformation of biotite to chlorite in some samples. Accessory minerals are opaque minerals, such as magnetite and pyrite.

Correlation and Age

The Crabtree terrane continues to the north of the Tar River area in the Kittrell and Henderson quadrangles (Grimes, 2000; Blake, 2001). Blake and others (2002) mapped the Crabtree terrane south of the Tar River area. The Middle Creek Gneiss unit trends to the north and south and may be analogous to the units of Grimes (2000) and Blake and others (2002). The age for the Middle Creek Gneiss has not yet been determined, but its relationship to the surrounding units suggests a late Proterozoic to Cambrian age.

Middle Creek Amphibolite (ЄZmca)

The Middle Creek Amphibolite is a mappable mafic body that occurs along the westernmost boundary of the Crabtree terrane. It is a light to dark grayish black, fine- to medium-grained, well-foliated and lineated amphibolite.

Petrographic Relationships

In thin section, the primarily minerals for the Middle Creek Amphibolite are hornblende and plagioclase. Hornblende is interlayered plagioclase and both are dynamically recrystallized with a hornblende nematoblastic lineation. Secondary chlorite occurs from reaction replacement of hornblende. Accessory minerals are magnetite and pyrite.

Correlation and Age

The Middle Creek Amphibolite continues to the north and terminates with the Grimes (2000) field area, but to the south it terminates in the Tar River area and is not seen to the south (Blake and others, 2002). The age of the Middle Creek Amphibolite is uncertain, but its relationship to the Middle Creek Gneiss and the surrounding units suggests a late Proterozoic to Cambrian age.

Talc actinolite chlorite rock (ЄZcu)

An outcrop of metaultramafic rock occurs within the Crabtree terrane. This body crops out on an unimproved logging road just east of the Wilton pluton and the Middle Creek Amphibolite. Total extent of the outcrop of these metaultramafic rocks is difficult to determine due to the poor exposure. The metaultramafic rock is a talc actinolite chlorite rock and appears light to dark green, fine- to medium-grained in outcrop. Weathered pieces of chlorite and magnetite are common in the soil with this unit.

Petrographic Relationships

This unit contains talc, chlorite, and actinolite in varying amounts. Thin sections contain idioblastic to subidioblastic porphyroblastic prisms of actinolite with minor amounts of talc and chlorite. Magnetite is an accessory mineral.

Correlation and Age

No other metaultramafic rocks have been mapped within the Crabtree terrane on the western flank of the Wake-Warren anticlinorium. The metaultramafic rocks are common within the Falls Lake terrane and the Carolina terrane as well as the Raleigh terrane (this study).

Raleigh Terrane

The Raleigh terrane is mainly composed of interlayered felsic, intermediate, and mafic gneiss that outcrops in approximately 25% of the field area (Figure 5; Plate 1) and is known as the Raleigh Gneiss (Parker, 1979; Farrar, 1985a, b; Stoddard and others, 1991). Small pods of metaultramafic rocks are found within the Raleigh Gneiss. Dikes of granite pegmatite, graphic granite, biotite granite intrude the Raleigh terrane. The Falls Leucogneiss occurs between the Raleigh Gneiss and the Crabtree terrane and, in this study, is considered to be part of the Raleigh terrane.

Raleigh Gneiss (ЄZrg)

The Raleigh Gneiss comprises approximately 95% of the Raleigh terrane and occurs to the east of the Falls Leucogneiss. The Rolesville batholith truncates the gneiss farther to the east. The Raleigh Gneiss is compositionally and complexly interlayered (Figure 15) and is separated into three distinct layers that include, a biotite hornblende gneiss, a biotite gneiss, and a biotite white mica gneiss. The Raleigh Gneiss ranges in appearance from a dark grayish-black to light tan or grayish-white. The best exposure of the Raleigh Gneiss occurs in creeks and along the Tar River. The Raleigh Gneiss weathers to a gravelly sand.

Petrographic Relationships

The mafic portion of the Raleigh Gneiss is a biotite hornblende gneiss and amphibolite gneiss that contains primarily hornblende with lesser amounts of biotite and plagioclase. Both the biotite and hornblende are layered along with quartz and plagioclase, giving the rock a gneissic foliation. Hornblende crystals are nematoblastic. Some biotite crystals display reaction replacement to chlorite. Plagioclase has undergone saussuritization and sericitization. The accessory minerals are sphene and opaque minerals such as pyrite.

The intermediate composition of the Raleigh Gneiss is a biotite gneiss that contains biotite, plagioclase, and quartz. Interlayers of biotite and plagioclase/quartz produce a gneissic foliation at the microscale. These interlayers also develop a mineral aggregate lineation. Plagioclase has undergone saussuritization and sericitization. Accessory minerals are sphene and opaque minerals such as pyrite.

The felsic composition of the Raleigh Gneiss is a biotite white mica gneiss that contains biotite, white-mica, plagioclase, microcline, and quartz. White mica is the dominant phyllosilicate and occurs along with small biotite crystals. Some biotite crystals display reaction replacement to chlorite. Both plagioclase and microcline are sericitized. Accessory minerals are opaque minerals such as pyrite.

Correlation and Age

The Raleigh Gneiss has been mapped to the north (Grimes, 2000) and the south (Blake and others, 2002) of the Tar River area. Raleigh Gneiss samples yield late

Figure 15: Outcrop photograph of the Raleigh Gneiss on US Hwy 1 about 0.5 km south of Franklinton, NC. The photograph shows intermediate Raleigh Gneiss with folded granitic intrusions. The scale bar is 15.24 cm long.

Proterozoic to Cambrian 461-546 Ma $^{207}Pb/^{206}Pb$ zircon ages (Goldberg, 1994; Horton and Stern, 1994).

Talc chlorite actinolite rock (ЄZru)

Three small bodies of metaultramafic rock occur within the Raleigh Gneiss. These bodies are confined to the mafic layers. Total extent of the outcrop of these metaultramafic rocks is difficult to determine due to the poor exposure. The metaultramafic rock is a talc chlorite actinolite rock and appears light to dark green, fine- to medium-grained in outcrop.

Petrographic Relationships

The metaultramafic rock contains talc, chlorite, and actinolite in varying amounts. Thin sections contain idioblastic to subidioblastic porphyroblast needles of actinolite with minor amounts talc and chlorite. Accessory minerals are opaque minerals such as magnetite.

Correlation and Age

Only a few exposures of metaultramafic rock in the Raleigh terrane have been mapped. Some have been described outcropping to the south of the Tar River area (Stoddard, oral communication), but none have been mapped and documented. Origin and age of these metaultramafic rocks in the Raleigh terrane has not been determined to date but are possibly enclaves within the Raleigh Gneiss.

Falls Leucogneiss (ЄZflg)

The Falls Leucogneiss forms an elongate body that extends from the south to the north of the field area (Figure 5; Plate 1). The Falls Leucogneiss is in contact with the Middle Creek Gneiss of the Crabtree terrane to the west and the Raleigh Gneiss to the east. The Falls Leucogneiss has a constant thickness of 500 meters throughout the field area. Many outcrops of the Falls Leucogneiss are resistant to weathering and form large tabular boulders (Figure 16). The Falls Leucogneiss is a pink-gray to orange-tan, fine- to medium-grained, weakly to moderately foliated, strongly lineated, leucocratic (CI<5), biotite-magnetite granitic gneiss.

Petrographic Relationships

At the microscale, the Falls Leucogneiss has a granoblastic texture with a gneissic layering. Primary minerals of the Falls Leucogneiss are microcline, quartz, and plagioclase. Accessory minerals are biotite and magnetite. The Falls Leucogneiss is leucocratic (CI>5) due to the small amount of biotite. Microcline and plagioclase display sericitization and the biotite displays reaction replacement to chlorite. A mineral stretching lineation of quartz, feldspar, and magnetite minerals in the Falls Leucogneiss produces an L-tectonite fabric.

Correlation and Age

This unit is mapped along the western flank of the Wake-Warren anticlinorium where it thickens and thins out in various areas and finally pinches out in the Henderson quadrangle (Blake, 2001). The protolith for the Falls Leucogneiss is thought to be

Figure 16: Photograph of an outcrop of the Falls Leucogneiss. The Falls Leucogneiss is resistant to erosion and commonly occurs as large elongate boulders that crop out on hillsides, road cuts, creeks, and along the Tar River.

granitic intrusion. The Falls Leucogneiss yields discordant $^{207}Pb/^{206}Pb$ zircon crystallization dates of 545-543 ± 20 Ma (Caslin and others, 2001) (Blake and others, 2001). These dates place the age of the Falls Leucogneiss from the late Proterozoic to Cambrian.

METAMORPHISM AND REGIONAL CORRELATIONS

Introduction

This chapter focuses on an overview of metamorphic events that affected the western flank of the Wake-Warren anticlinorium, and produced the metamorphic mineral assemblages within the rocks types of the Tar River area. The metamorphic events and mineral assemblages for the western flank are defined to add a regional perspective to the metamorphism of the Tar River area.

The rocks along the western flank (Figure 2) have undergone potentially four metamorphic events (Table 1). Farrar (1984) observed a Grenville-age metamorphic event (M_g) in eastern Virginia that is thought to affect the northern portion of the Wake-Warren anticlinorium, although no evidence has been found for M_g metamorphic assemblages in North Carolina. A metamorphic event (M_e) that is possibly pre-Taconic, achieved the greenschist to amphibolite facies and is observed within the four types of enclaves of the Gibbs Creek pluton in the northernmost Carolina terrane. A regional prograde Taconic metamorphic event (M_1) is observed in the structurally higher Carolina, Spring Hope, and Roanoke Rapids terranes. A regional prograde Alleghanian (M_2) is the most prominent metamorphism on the western flank and is observed within the structurally lower Falls Lake, Crabtree, Raleigh, and Triplet terranes, and locally in eastern portions of the Carolina terrane. Local contact metamorphism is observed adjacent to some of the Alleghanian plutons that intrude the Spring Hope terrane (Gaughan, 1999; Gaughan and Stoddard, 2003). Local areas of retrograde metamorphism have also been observed.

Table 1: Metamorphic events proposed to have affected the terranes of the western flank of the Wake-Warren anticlinorium and the Tar River area. These metamorphic events are based on work from Farrar (1984), Kish and others (1979), Russell and others, (1985), Glover and others, (1983), Stoddard and others (1991), and this study.

Metamorphic Event	Metamorphic Facies Experienced	Terranes with Metamorphism	Related Orogenic Event
M_2	Greenschist to Amphibolite (Kyanite-Garnet-sillimanite zone)	Falls Lake terrane, Crabtree terrane, Raleigh terrane	Alleghanian
M_1	Greenschist (Chlorite to Biotite zone)	Carolina terrane, Spring Hope terrane, Roanoke Rapids terrane	Taconic
M_e	Greenshist to Amphibolite (Garnet to biotite zone)	Enclaves within the Carolina terrane	Virgilina (?)
M_g	Upper Amphibolite to Granulite (Orthopyoxene zone)	Goochland terrane, Macon terrane (?), Raleigh terrane (?)	Grenville (?)

Metamorphic Events

Metamorphic events for the Tar River area are described below along with an M_g event. Mineral assemblages consistent with the M_g development in a granulite facies event were not observed in the Tar River area. The silicified ridge creates a major discontinuity within the Tar River area. This ridge separates the M_1 event from the M_2 event (Figure 17).

M_g: Grenville Event

Farrar (1984; 1985b) observed an M_g Grenville metamorphic event that affected rocks of the Goochland terrane in the eastern Virginia Piedmont. This event metamorphosed 1.1 Ga Grenville-age basement rock (Goochland terrane) to the sillimanite zone of the upper amphibolite facies and into the orthopyroxene zone of the granulite facies. Farrar (1985a) states that relict assemblages of M_g are found in the northern portions of the Raleigh Gneiss and the Macon Formation. These M_g assemblages consist of coarse-grained sillimanite or coarse-grained sillimanite + garnet that have been partially replaced by white mica + chlorite ± staurolite ± chloritoid (Farrar, 1985a). In the northern portion of the Raleigh Gneiss, there is a clinopyroxene-bearing biotite-epidote-hornblende-quartz-plagioclase gneiss in which the epidote + amphibole + quartz has partially replaced the clinopyroxene + plagioclase (Farrar, 1985a).

The M_g assemblages in the rocks of the Goochland terrane in Virginia include orthopyroxene ± garnet ± clinopyroxene granulite gneiss and clinopyroxene + garnet

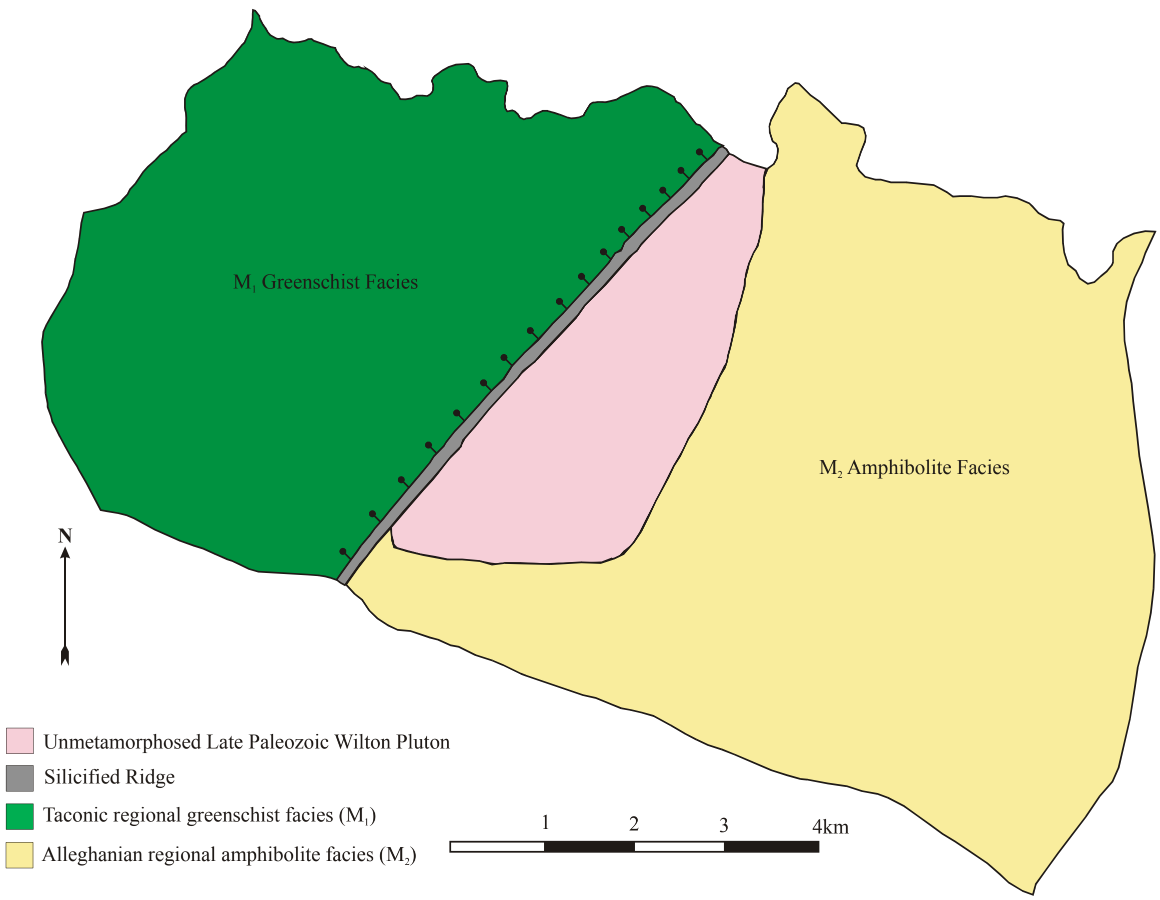


Figure 17: A metamorphic facies map of the Tar River area showing the regional metamorphic events. Enclaves observed within the Gibbs Creek pluton west of the silicified ridge display the effects of the M$_e$ metamorphism.

granulite gneiss. The M_g pelitic assemblage in the Goochland terrane contains coarse sillimanite + garnet ± K-feldspar. Farrar (1985a) states that the occurrence of these assemblages in the Raleigh terrane are used to estimate the aerial extent of the Grenville-age basement known as the Goochland terrane.

However, the metamorphic assemblages of the Raleigh terrane do not contain orthopyroxene and do not represent a granulite facies metamorphism. Stoddard and others (1985, 1991) also suggest that textural relationships of sillimanite in pelites and clinopyroxene in amphibolite are porphryoblasts related to the latest Alleghanian metamorphism. In this study, evidence for M_g mineral assemblages was also not observed within the Tar River Area.

M_e: Enclave Metamorphism (Pre-Taconic?)

A greenschist to amphibolite facies metamorphism, M_e, occurs within the enclaves found within Gibbs Creek pluton that crops out in, and just to the north (Blake and others, 2003) and south of the Tar River area (Blake and others, 2002). These enclaves include the: 1) Type 1 greenstone enclaves, which contain a chlorite + epidote + plagioclase ± actinolite assemblage that overprints relict plagioclase + hornblende + clinopyroxene; 2) Type 2 are foliated amphibolite enclaves, which contain a plagioclase + chlorite ± epidote ± sericite assemblage that overprints plagioclase + hornblende; 3) Type 3 metaultramafic rock enclaves, which contain a talc + serpentine ± actinolite assemblage; and 4) Type 4 foliated metagranitoid enclaves, which contain quartz + chlorite ± sericite ± epidote that overprints plagioclase + orthoclase + biotite. M_e is observed only in the enclaves within the Gibbs Creek pluton, although these enclaves also contain some overprint from the younger M_1 event as well.

M_1: Taconic

A regional greenschist facies metamorphism (M_1) occurred during the Taconic orogeny (Kish and others, 1979). M_1 affected the structurally higher portions of the western flank and the rocks that retain this metamorphism are exposed within the Carolina, Spring Hope, and Roanoke Rapids terranes. M_1 mineral assemblages occur at the greenschist facies (chlorite to biotite zone). These assemblages include albite + quartz + white mica + epidote ± calcite ± opaque minerals ± garnet in the felsic metavolcanic rocks and metasedimentary rocks, quartz + albite + muscovite + chlorite + epidote + opaque minerals ± zircon ± hematite ± tourmaline ± titanite in metamudstone and phyllite, and epidote + quartz + albite ± chlorite ± actinolite ± calcite ± opaque minerals in mafic metavolcanic and metasedimentary rocks (Farrar, 1985a).

In the Tar River area, the M_1 regional metamorphism occurs to the west of the silicified ridge and affects the northeastern Carolina terrane. The Gibbs Creek pluton and the foliated metagranodiorite are intermediate in composition and contain the M_1 assemblage quartz + chlorite + white mica + sericite + epidote. The metagabbro represents a mafic portion of the Carolina terrane and its M_1 mafic assemblage is actinolite + chlorite + epidote. All four types of enclaves with the M_e metamorphism have been overprinted with the M_1 metamorphism. While it is difficult to distinguish between the M_e and M_1 metamorphism within the enclaves, the foliated enclaves are separate from the unfoliated host pluton. The Ruin Creek Gneiss lies west of the silicified breccia and contains the M_1 assemblage quartz + chlorite + white mica + epidote + sericite that overprints microcline + plagioclase ± biotite.

M_2: Alleghanian

The latest regional metamorphic event (M_2) occurred during the Alleghanian orogeny (Russell and others, 1985; Glover and others, 1983) and affected the structurally lower terranes following their juxtaposition to one another (Stoddard and others, 1991). This event ranged from the chlorite zone of the greenschist facies to the kyanite zone of the amphibolite facies metamorphism. On the western flank of the Wake-Warren anticlinorium, metamorphic grade increases toward the east. The rocks that experienced the highest metamorphic effects from M_2 are the structurally lowest and lie within the Falls Lake, Crabtree, and Raleigh terranes. The lowest grade of M_2 metamorphism occurs at the chlorite zone, making it indistinguishable from M_1 in the greenschist facies, Carolina, Springhope, and Roanoke Rapids terranes (Farrar, 1985a). In pelitic assemblages, quartz + albite + white mica + chlorite + opaque minerals recrystallize to chloritoid + quartz + white mica + chlorite + opaque minerals ± biotite ± albite in the upper greenschist facies (Farrar, 1985a). The presence of staurolite + garnet + biotite + quartz + plagioclase + graphite mark the amphibolite facies in the pelitic rocks of the Crabtree terrane. The highest pelitic assemblages are quartz + white mica + biotite + garnet + plagioclase + staurolite + kyanite + opaque minerals ± chlorite ± zircon ± apatite, which occur just east the Falls Leucogneiss in the northernmost Raleigh terrane near the Virginia-North Carolina border (Farrar, 1985a).

In the Tar River area, the M_2 regional metamorphism occurs east of the silicified ridge and affects the Falls Lake, Crabtree, and Raleigh terranes. The Falls Lake Schist of the Falls lake terrane contains the M_2 assemblage quartz + white mica + biotite + garnet ± chlorite ± sericite. The Middle Creek Gneiss contains felsic, intermediate, and mafic composition gneisses. The felsic and intermediate gneiss assemblage consists of quartz + biotite + white mica ± chlorite ± epidote ± sphene ± sericite. The mafic gneiss and the Middle Creek Amphibolite assemblage contains quartz + hornblende + biotite ± sericite ± chlorite ± epidote. Chlorite replaced the hornblende, and sericite and epidote replaced plagioclase and microcline.

The Falls Leucogneiss represents a leucocratic unit with the M_2 assemblage sericite ± chlorite ± biotite that overprints quartz + microcline + plagioclase + magnetite. The Raleigh Gneiss contains composition layers that range from felsic to intermediate to mafic. The felsic and intermediate assemblage consists of quartz + biotite + white mica ± chlorite ± epidote ± sphene ± sericite. The mafic assemblage contains quartz ± biotite ± sericite ± chlorite ± epidote. Chlorite replaced the hornblende and sericite and epidote replaced plagioclase and orthoclase. Metaultramafic enclaves appear within the mafic units of the Raleigh Gneiss and the Middle Creek Gneiss and contain the assemblage actinolite + chlorite + talc.

Local retrograde effects may exist in the rocks units on both sides of the silicified ridge. The presence of epidote and sericite in the feldspar and chlorite replacing biotite, hornblende, and garnet may mark the retrograde effects. Possibly some retrograde effects occur within the units east of the silicified breccia. These units display chlorite replacing biotite and plagioclase and microcline displaying sericitization and saussuritization.

GEOCHEMISTRY

Introduction

The western flank of the Wake-Warren anticlinorium contains many structures that overprint and juxtapose terranes that share a similar volcanic island-arc affinity in the northeastern Carolina Zone (Hibbard and Samson, 1995; Hibbard and others, 2002). The relationship between these terranes is not clearly understood and similar rock types are present in more than one terrane, although they commonly vary in crystal size, degree of dynamic recrystallization, and metamorphic grade. Similarities in mineralogical appearance and relict textural features between the units of the Carolina terrane within the Tar River area and the Falls Lake terrane to the south were noted during field mapping.

The greenschist facies Carolina terrane within the Tar River area contains the Gibbs Creek pluton, a metatonalite with subordinate metagranodiorite that contains enclaves of metaultramafic rock, amphibolite, and greenstone. To the south, the amphibolite facies Falls Lake terrane contains a matrix of white mica and biotite gneiss and schist, hornblende gneiss, amphibolite, and blocks and pods of metamorphosed ultramafic rocks (Moye, 1981). Both terranes display a similar block-in-matrix appearance, but are separated by a silicified ridge that defines a metamorphic discontinuity between the two terranes.

Because of similarities between these two terranes in matrix mineral assemble and the presence of enclaves, the objectives for this geochemical study were to: 1) sample the Gibbs Creek pluton and characterize its major and trace element concentrations and to compare it to the geochemistry of the Falls Lake terrane, and 2) characterize and compare metamafic enclaves from both terranes to evaluate if any similarities exist, 3) address whether the Cary sequence in the southeasternmost Carolina terrane (Parker, 1979; Farrar, 1985a) has a geochemical affinity with the Falls Lake terrane and the Carolina terrane in the Tar River area, and 4) evaluate the geochemical relationship of the Middle Creek Gneiss from the Crabtree terrane to examine any geochemical affinities across terrane boundaries.

Methodology

The four samples collected from the Tar River area are: 1) TR01-218, a biotite gneiss, collected east of the silicified ridge from an exposure on the Tar River within the Middle Creek Gneiss; 2) TR01-248, collected from the Gibbs Creek pluton on the Tar River; 3) TR01-396, collected from boulders of Gibbs Creek pluton; and 4) TR01-526, collected from a stream exposure of Gibbs Creek pluton. The three samples of the Gibbs Creek pluton represent the matrix rock for the Carolina terrane within the Tar River area. The Middle Creek Gneiss sample (TR01-218) has a relict igneous texture and was collected to define its geochemical signature in order to evaluate the potential for a geochemical affinity across the silicified ridge.

Two additional samples collected just north of Tar River area were processed and prepared in a similar manner by Dr. David E. Blake for a 2002 North Carolina Geological Survey STATEMAP project (Blake and others, 2003). These samples are WT02-4492, from the Gibbs Creek pluton and WT02-3560, an amphibolite enclave within the pluton.

For comparison, sample WR99-2891, was collected from a type outcrop of the Falls Lake terrane matrix rock in the Bayleaf 1:24,000 quadrangle. It is part of a larger suite of rocks collected by Dr. David Blake in 1999 to study the western flank geochemistry. Another sample, FLM-M is from the Falls Lake terrane and is an amphibolite enclave collected by Moye (1981).

Comparison data for the easternmost Carolina terrane was derived from unpublished Master's theses of Heller (1996), Phelps (1998), and Grimes (2000) and a suite of unpublished North Carolina Geological Survey geochemical analyses from 1993 to 2002 (Blake and Stoddard, 2004).

The samples for this study were prepared in the UNCW Earth Science Petrology Preparation Laboratory. Whole rock geochemical samples were cleaned of any weathering rinds or debris. The cleaned samples were broken into smaller pieces with a 600 lb hydraulic jack and crushed into chips using a steel-plated jaw crusher. These chips were washed three times using an ultrasonic cleaner filled with deionized water to remove loose particles. A final rinse of deionized water was applied and the samples were oven-dried. The samples were ground into powder using an aluminoceramic SPEX™ shatterbox and sent to XRAL laboratories (Don Mills, Ontario) for analysis of whole-rock major and trace elements. The chemical analyses reported were determined by a suite of techniques that included X-ray fluorescence, ICP mass spectrometry, neutron activation analysis, ICP/MS, and AA spectrophotometry.

Major Element Data

Major element data for the four Gibbs Creek samples (TR01-526, TR01-396, TR01-248, and WT02-4492) and the Middle Creek sample (TR01-218) are reported in Table 2. The major element chemistry is generally consistent among the samples. In Figure 18, Harker diagrams show a clustering of the major element data for the Gibbs Creek pluton samples with the exception of Na_2O vs. SiO_2. This variation (~1.5 wt% Na_2O) may reflect the degree of plagioclase alteration by sericitization and saussuritization. The Middle Creek Gneiss sample (TR01-218) is also similar in major element chemistry to the Gibbs Creek pluton samples except for higher Na_2O (~5 wt%), CaO (~4 wt%), and lower K_2O (~1.5 wt%) (Figure 18). These variations may reflect the difference in metamorphic grade between the amphibolite facies metamorphism of TR01-218 and the greenschist facies metamorphism of the Gibbs Creek pluton samples. The variations may also reflect aspects of the protolith geochemistry or may be a result of the proximity of TR01-218 to the Nutbush Creek fault zone.

The Falls Lake sample, WR99-2891, is similar in major element chemistry (Table 2) to the Gibbs Creek pluton samples. WR99-2891 is an amphibolite facies rock and has moderate of amounts of Na_2O, K_2O, Fe_2O_3, and MgO, reflecting an intermediate signature. This sample is the most SiO_2-rich of the study. The major element concentrations for this sample are comparable to the Gibbs Creek samples although there is a slight decrease in Al_2O_3 (~1 wt%) (Figure 18).

The major element data for the two amphibolitic enclaves is reported in Table 3. WT02-3560 is a greenschist facies enclave within the Gibbs Creek pluton and FLM-M is an amphibolite facies enclave within the Falls Lake terrane matrix. Both enclaves show a

Table 2: Geochemical data for the Gibbs Creek pluton, Falls Lake terrane matrix, and Middle Creek Gneiss samples. Not analyzed-na. Below detection-bd.

	Gibbs Creek pluton					Falls Lake terrane matrix		Middle Creek Gneiss
	TR01-248	TR01-396	TR01-526	WT02-4492		WR99-2891		TR01-218
SiO_2	65.6	65.3	63.9	64.38	SiO_2	68.60	SiO_2	64.8
TiO_2	0.798	0.837	0.885	0.79	TiO_2	0.70	TiO_2	0.895
Al_2O_3	15.6	15.9	16.1	16.3	Al_2O_3	14.60	Al_2O_3	15.70
Fe_2O_3	6.13	5.95	6.36	6.52	Fe_2O_3	5.50	Fe_2O_3	5.18
MnO	0.1	0.1	0.15	0.11	MnO	0.11	MnO	0.11
MgO	2.23	2.3	2.31	2.17	MgO	1.96	MgO	1.79
CaO	1.91	2.92	2.5	1.67	CaO	1.70	CaO	4.14
Na_2O	2.28	2.82	3.17	1.62	Na_2O	2.36	Na_2O	4.86
K_2O	3.05	3.03	2.8	3.32	K_2O	2.92	K_2O	1.55
P_2O_5	0.09	0.12	0.12	0.13	P_2O_5	0.08	P_2O_5	0.23
Cr_2O_3	bd	bd	bd	0.01	Cr_2O_3	bd	Cr_2O_3	bd
LOI	2.45	0.90	1.60	2.75	LOI	1.55	LOI	0.80
TOTAL	100.40	100.30	100.10	99.89	TOTAL	100.30	TOTAL	100.20
Sc	16	16	22	bd	Sc	12	Sc	14
Cr	47	67	70	bd	Cr	54	Cr	16
Co	17.4	15.3	19.6	13.3	Co	13	Co	5.9
Ni	31	33	30	23	Ni	17	Ni	9
Cu	98.2	69.8	15.4	72	Cu	20.1	Cu	28.9
Zn	119	85.8	101	85	Zn	57.8	Zn	74.5
Ga	na	na	na	19	Ga	na	Ga	na
Br	<1	1	<1	bd	Br	2	Br	<1
V	94	100	97	90	V	94	V	101
Rb	117	117	110	111	Rb	89	Rb	44
Sr	169	194	228	154	Sr	195	Sr	389
Y	32	31	35	27.3	Y	37	Y	38
Zr	277	241	254	186	Zr	207	Zr	274
Nb	16	19	16	11	Nb	14	Nb	8
Sb	0.6	<0.1	0.2	bd	Sb	<0.1	Sb	0.6
Cs	4.9	6.3	4.5	7	Cs	2.7	Cs	2.1
Ba	553	548	471	576	Ba	694	Ba	503
La	42.8	41.4	36.4	40.2	La	40.2	La	27.1
Ce	71	87	77	83.6	Ce	77	Ce	65
Nd	27	51	49	36.8	Nd	32	Nd	33
Sm	6.83	6.31	6.47	7.5	Sm	6.93	Sm	6.67
Eu	1.45	1.97	1.73	1.41	Eu	1.4	Eu	2.82
Tb	0.6	0.6	1.1	1.14	Tb	1.1	Tb	1.3
Yb	3.78	3.08	3.98	3.5	Yb	3.6	Yb	3.68
Lu	0.55	0.58	0.54	0.55	Lu	0.55	Lu	0.64
Hf	6.5	6.9	6.5	6	Hf	5.9	Hf	6.9
Ta	1.4	<0.5	1.1	0.7	Ta	0.8	Ta	1.4
Th	12.5	12	9.7	10.1	Th	12	Th	4
U	1	1.2	0.2	2.25	U	1.7	U	3.1

Table 3: Geochemical data for the Gibbs Creek enclave, WT02-3560 and the Falls Lake terrane enclave FLM-M. Not analyzed-na. Below detection-bd.

Gibbs Creek Enclave		Falls Lake T. Enclave	
	WT02-3560		FLM-M
SiO_2	48.84	SiO_2	48.70
TiO_2	1.67	TiO_2	1.95
Al_2O_3	13.4	Al_2O_3	12.30
Fe_2O_3	13.87	Fe_2O_3	14.90
MnO	0.22	MnO	0.32
MgO	7.06	MgO	6.70
CaO	10.76	CaO	10.20
Na_2O	2.11	Na_2O	0.91
K_2O	0.38	K_2O	0.27
P_2O_5	0.13	P_2O_5	0.18
Cr_2O_3	0.01	Cr_2O_3	
LOI	1.00	LOI	1.10
TOTAL	99.48	TOTAL	97.53
Sc	bd	Sc	42.5
Cr	bd	Cr	89
Co	41.3	Co	44
Ni	51	Ni	41
Cu	141	Cu	3.3
Zn	172	Zn	112
Ga	17	Ga	
Br	bd	Br	2.7
V	380	V	396
Rb	6.9	Rb	bd
Sr	90.2	Sr	123
Y	35.2	Y	44
Zr	82	Zr	123
Nb	2	Nb	bd
Sb	bd	Sb	0.9
Cs	0.5	Cs	bd
Ba	26.9	Ba	51
La	3.5	La	8
Ce	11.4	Ce	21
Nd	11.3	Nd	13
Sm	4.2	Sm	4.27
Eu	1.26	Eu	1.61
Tb	1.11	Tb	0.8
Yb	4.2	Yb	4.34
Lu	0.71	Lu	
Hf	3	Hf	4.1
Ta	<0.5	Ta	
Th	0.2	Th	
U	<0.05	U	

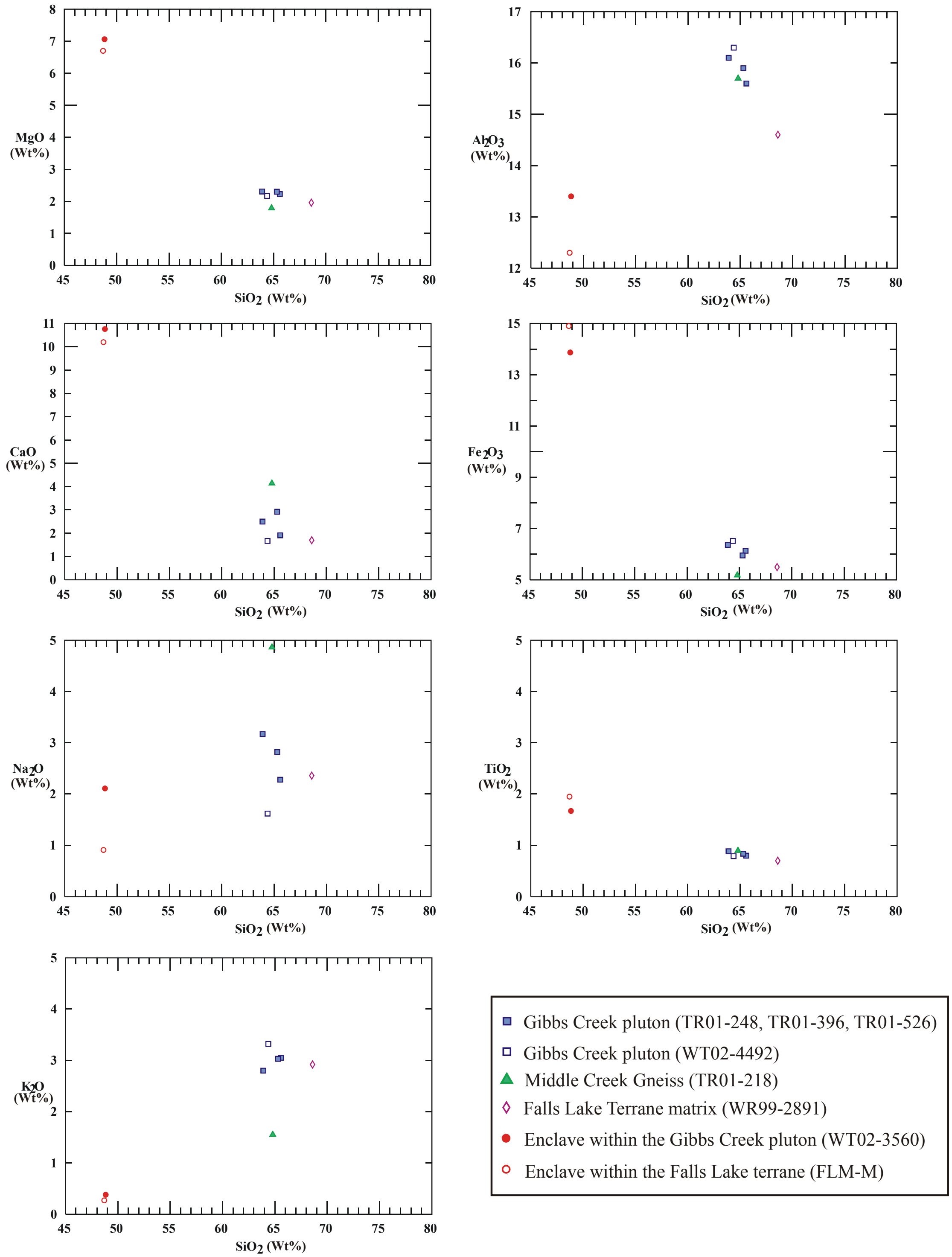


Figure 18: Harker diagrams of samples from the Gibbs Creek pluton, Middle Creek Gneiss, Falls Lake terrane matrix, Gibbs Creek pluton enclave, and the Falls Lake terrane enclave.

mafic signature in the major element data (Table 3; Figure 18). Both have low amounts of SiO_2 (~49 wt%), Na_2O, K_2O, and P_2O_5 and higher amounts of MgO (~7 wt%) and CaO (~10.5 wt%). They differ slightly from one another in Na_2O and in Al_2O_3 (Figure 18).

The samples were plotted on a LaBas and others (1986) total alkali to silica (TAS) plot (Figure 19). The four Gibbs Creek pluton samples and TR01-218 plot in a cluster within the dacite field. These samples have similar amounts of SiO_2, but differ in the amounts of $Na_2O + K_2O$. The Falls Lake terrane sample, WR99-2891, plots within the dacite field adjacent to the four Gibbs Creek pluton samples and TR01-218, but has a higher SiO_2 concentration. The mafic enclaves, FLM-M and WT02-3560, have very low amounts of $Na_2O + K_2O$ and SiO_2 and plot within the basalt field. Both enclaves contain approximately the same amount of SiO_2, but WT02-3560 contains approximately 2 wt% more $Na_2O + K_2O$.

A quartz-alkali feldspar-plagioclase (QAP) ternary diagram was used to classify the rocks based on their mineralogic assemblage (Figure 20). The Gibbs Creek pluton samples, TR01-396 and TR01-526, plot within the granodiorite field. The remaining Gibbs Creek pluton samples, TR01-248 and WT02-4492, plot into the granite field, which could reflect the degree of secondary alteration of the feldspars. The Falls Lake terrane matrix sample,WR99-2891, plots just in the granite field near the granodiorite field. The biotite gneiss sample, TR01-218, plots in lower portion of the granodiorite field away from the Gibbs Creek pluton samples. The Gibbs Creek pluton enclave sample, WT02-3560, plots within the gabbro field. The Falls Lake terrane enclave

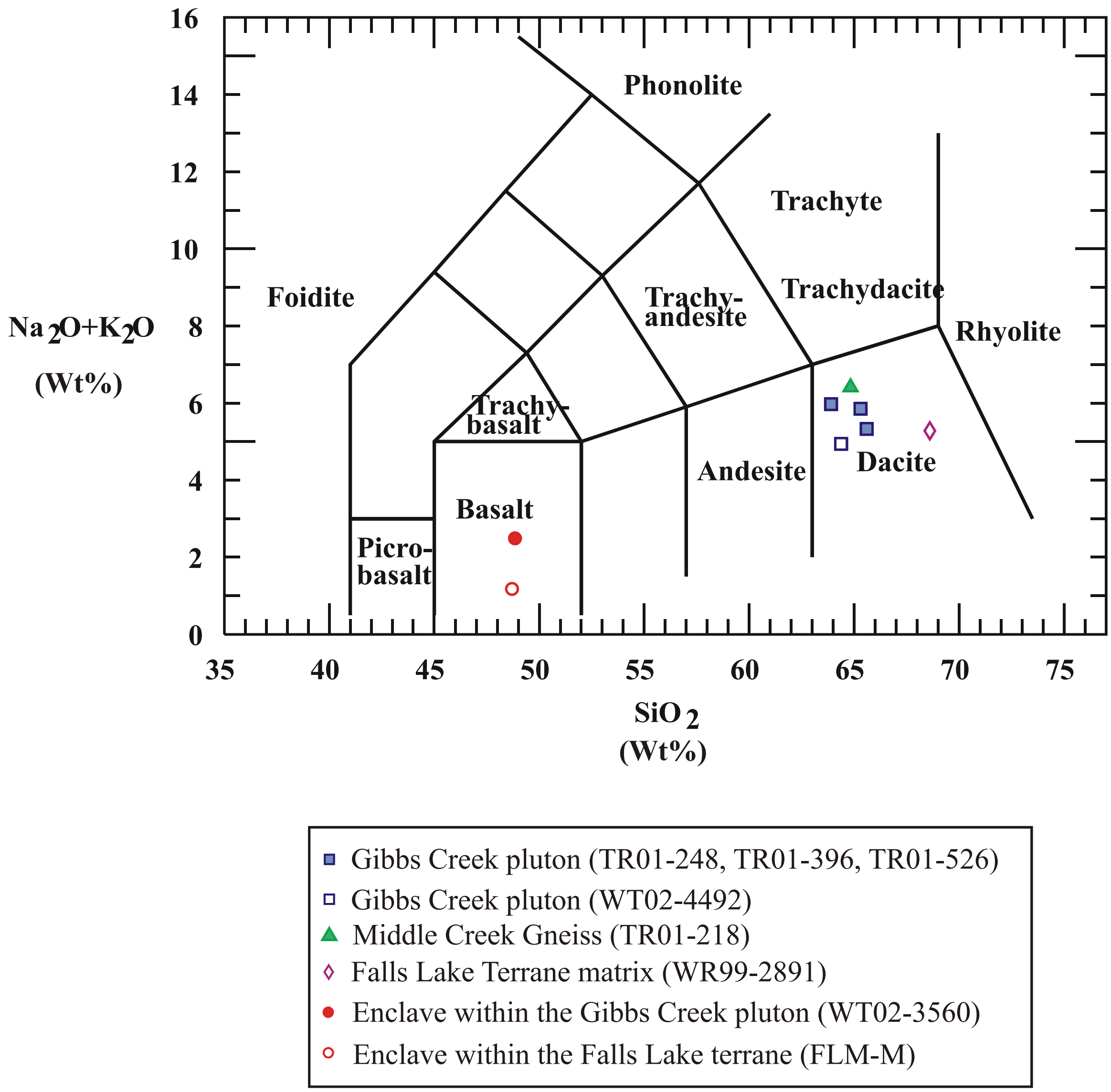


Figure 19: LaBas and others (1986) total alkali to silica (TAS) plot for the Gibbs Creek pluton, Middle Creek Gneiss, Falls Lake terrane matrix, and enclave samples.

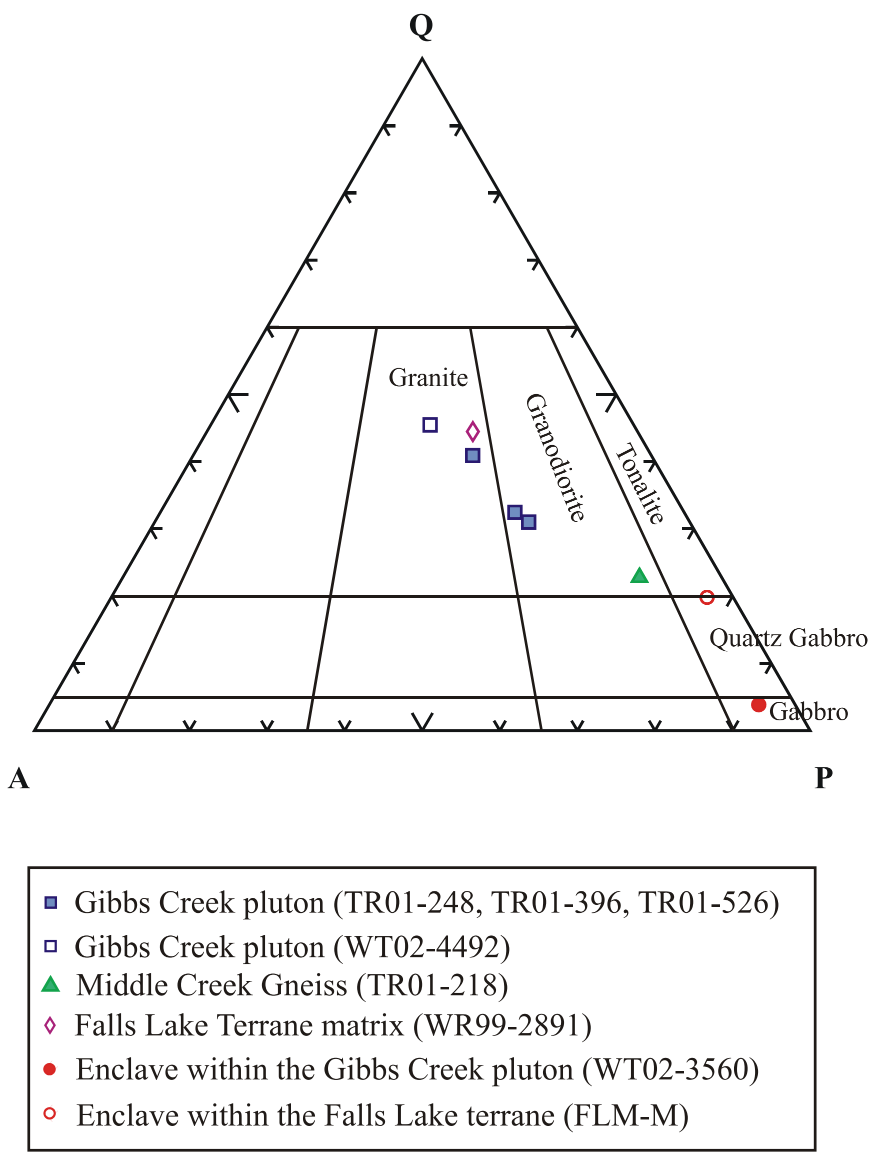


Figure 20: A QAP classification triangle for the Gibbs Creek pluton, Middle Creek Gneiss, Falls Lake terrane matrix, and enclave samples.

sample, FLM-M, plots in the quartz gabbro field showing a difference in the amount of quartz between the two enclaves.

Multi-element Discrimination Diagrams

Harker diagrams for the trace elements, Rb, Sr, V, Ni, and Cr, are shown in Figure 21. The Gibbs Creek pluton samples TR01-248, TR01-396, and TR01-526 show some variation in Sr and Cr, whereas the Cr data for WT02-4492 was below detection. Sample TR01-218 is elevated in Sr (~400 ppm) and is depleted in Rb (~50 ppm), Ni (~15-20 ppm), and Cr (~30-40 ppm) as compared to the other samples (Figure 21).

The Falls Lake terrane sample, WR99-2891, has similar amounts of Rb, Sr, V, Ni, and Cr compared to the Gibbs Creek samples, although it is the most SiO_2-rich sample (Figure 21). The two enclave samples differ from each other in Sr and Ni. The Cr data for the Gibbs Creek enclave sample, WT02-3560, was below detection. In addition, WT02-3560 only had a minor amount (6.9 ppm) of Rb (Figure 21). The Rb data for the Falls Lake terrane enclave FLM-M was below detection.

Using N-MORB-normalized Sun and McDonough (1989) multi-element discrimination diagrams, the Gibbs Creek pluton samples plot consistently together with only TR01-526 showing a depletion in U. These samples have an enrichment in the mobile/soluble large-ion lithophile (LIL) elements (1000X N-MORB) and are depleted in the immobile elements (Figure 22a). Nb displays a negative anomaly, a potential island-arc signature, while Pb shows a positive anomaly.

Comparing the Falls Lake terrane sample (WR99-2891) and the biotite gneiss sample (TR01-218) to the Gibbs Creek pluton samples reveals slight differences, but the

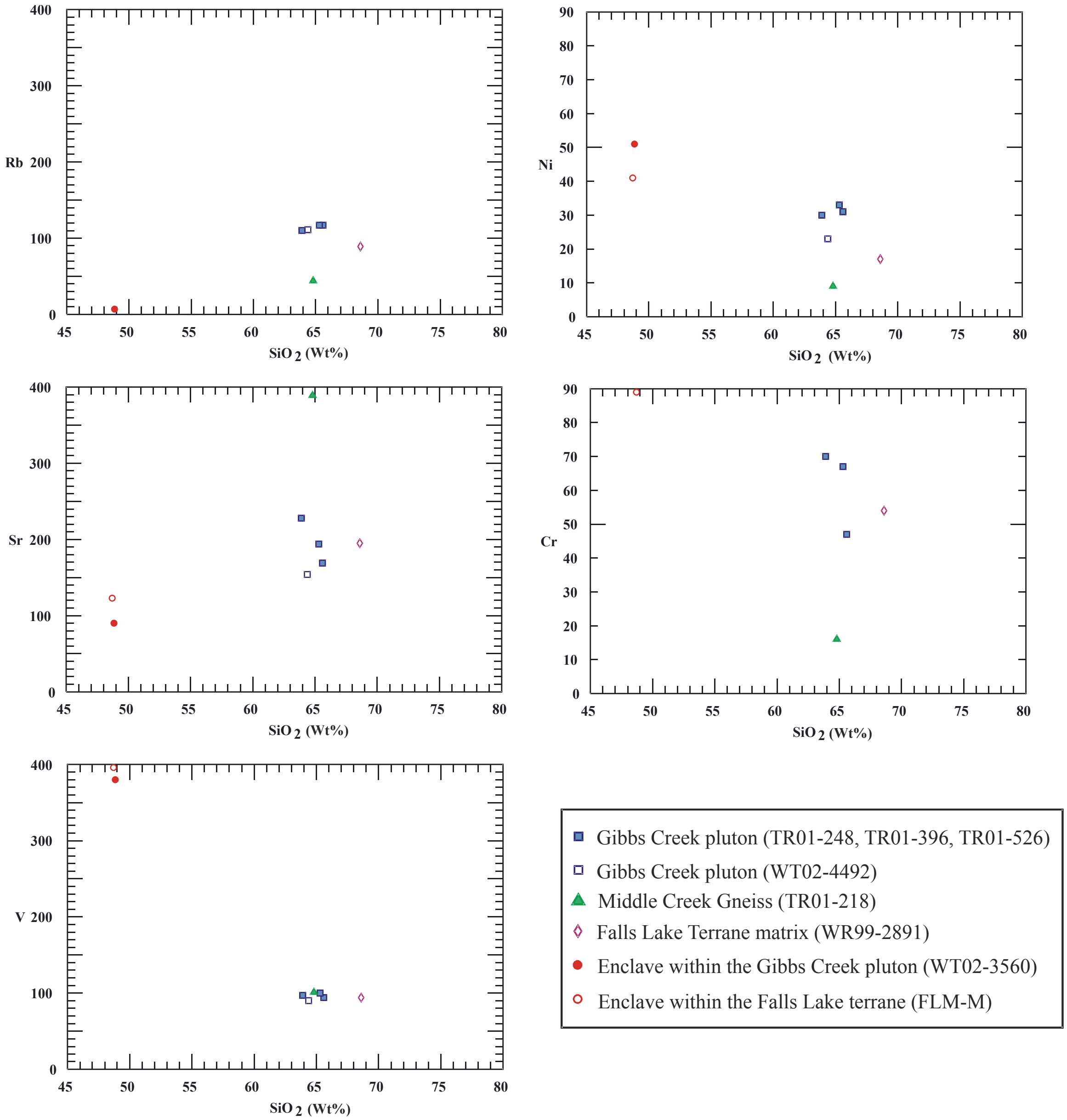


Figure 21: Harker diagrams of samples from the Gibbs Creek pluton, Middle Creek Gneiss, Falls Lake terrane matrix, Gibbs Creek pluton enclave, and the Falls Lake terrane enclave.

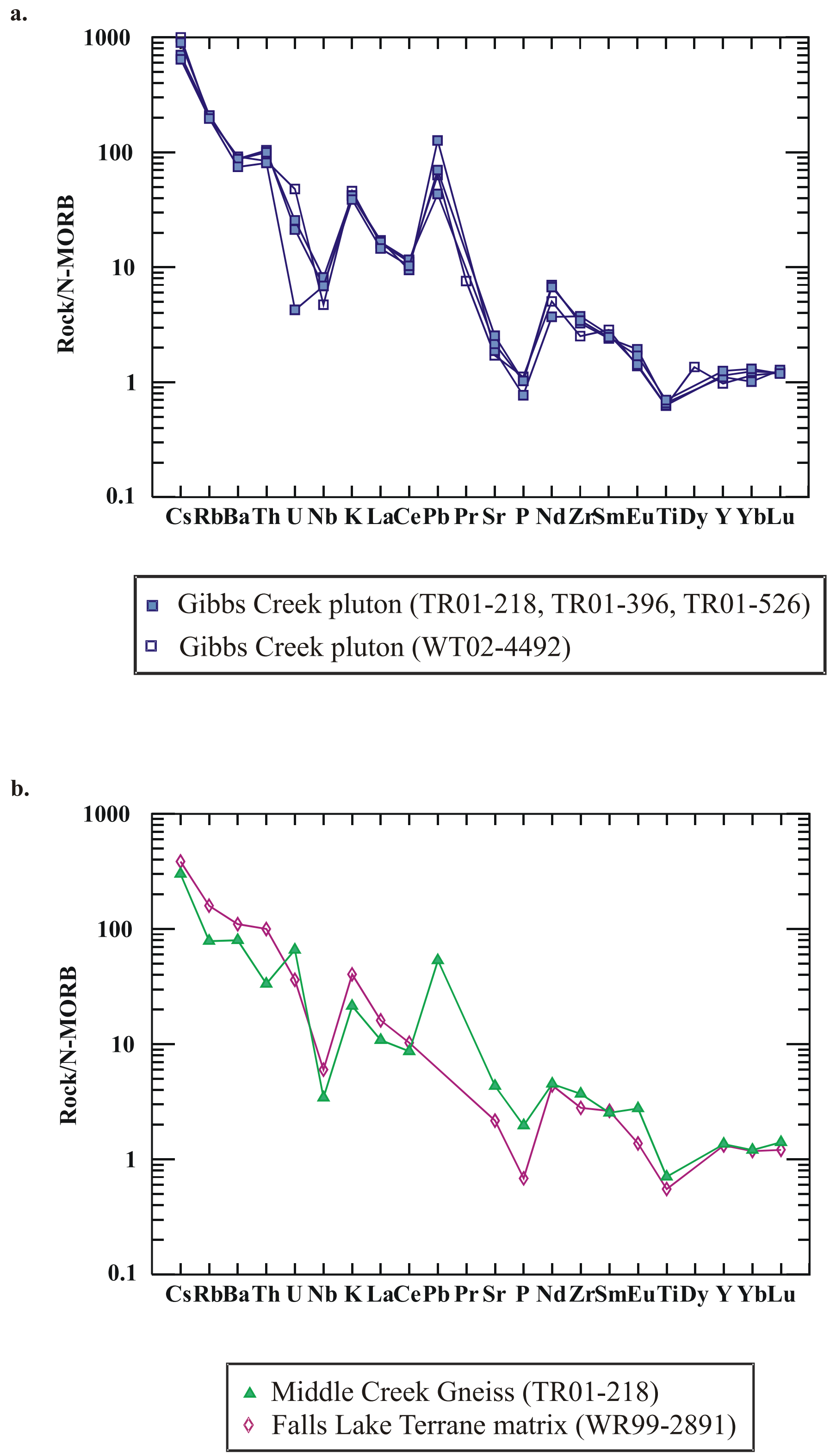


Figure 22: Sun and McDonough (1989) N-MORB-normalized multi-element diagrams for the: a) Gibbs Creek pluton samples, and b) Middle Creek Gneiss and Falls Lake terrane samples.

overall trend is comparable to the Gibbs Creek pluton samples (Figure 22b). TR01-218 and WR99-2891 have a decrease in Cs (~300 to 400X N-MORB) and Rb (~100X N-MORB), which is probably displaying the mobility of the elements due to the differences in metamorphic grade with the Gibbs Creek pluton samples. The samples show slight variances in P and Eu, while maintaining the negative Nb anomaly. Pb data for the Falls Lake terrane sample, WR99-2891, is < 2 ppm and no interpretation about the trend of this element can be determined.

The enclaves are very different from the rest of the samples, which was expected due to the major element compositional differences (Figure 23). These samples have trace element similarities with each other, but the FLM-M data of Moye (1981) is incomplete. Cs for WT02-3560 is lower than the Gibbs Creek pluton, Falls Lake terrane, and Middle Creek Gneiss samples. Both enclaves show a positive Pb anomaly and very consistent LIL elements (Sr to Lu; ~1X N-MORB). These samples, even with the incomplete Moye (1981) data set, are very different than the matrix rock and have potential to be very similar to one another, but it is equivocal with this data.

Rare Earth Elements (REE)

Using Nakamura (1974) chondrite-normalized rare earth element data (Table 2), the four Gibbs Creek pluton samples show a consistent trend with LREE enrichment (~100X chondrite) (Figure 24a). Sample WR99-2891 from the Falls Lake terrane and the Middle Creek Gneiss sample, TR01-218, are also LREE-enriched (~100X chondrite). These samples have a consistent flat trend in the HREE (30 to 40X chondrite) (Figure 24a). This pattern is typical for island-arc magmas. There is a slight variation in Eu,

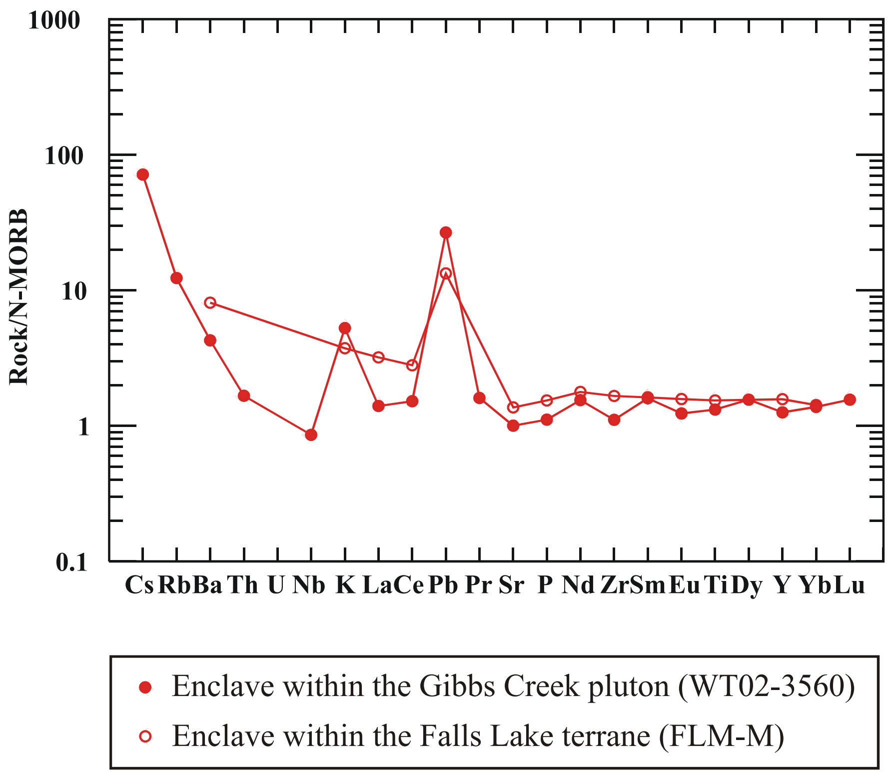
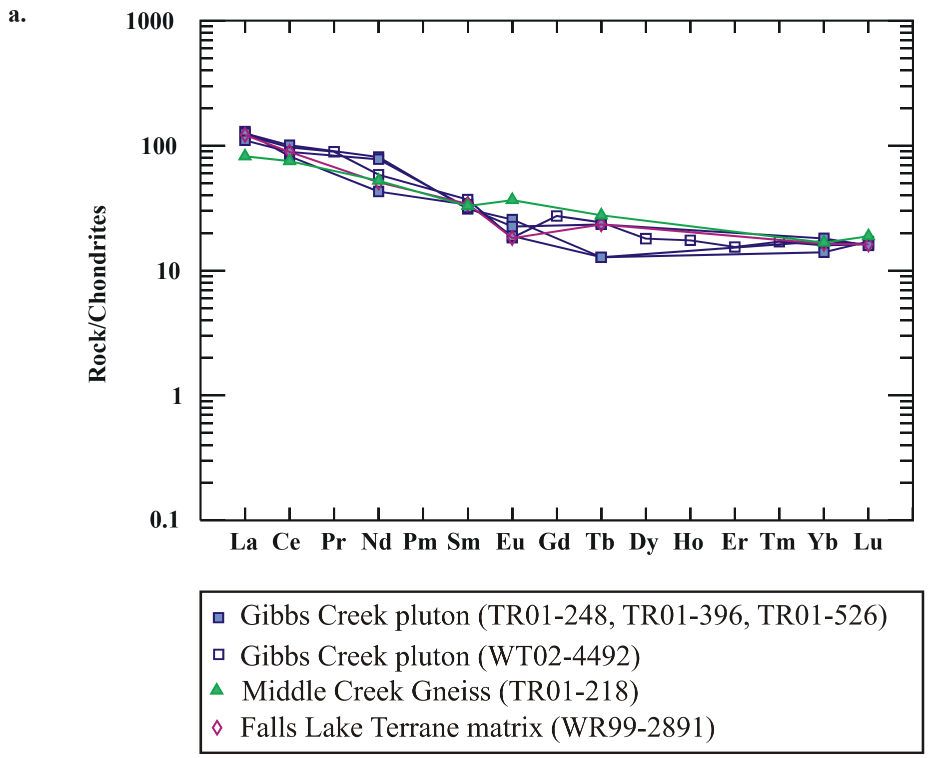


Figure 23: Sun and McDonough (1989) N-MORB-normalized multi-element diagram for the Gibbs Creek pluton enclave and the Falls Lake terrane enclave.



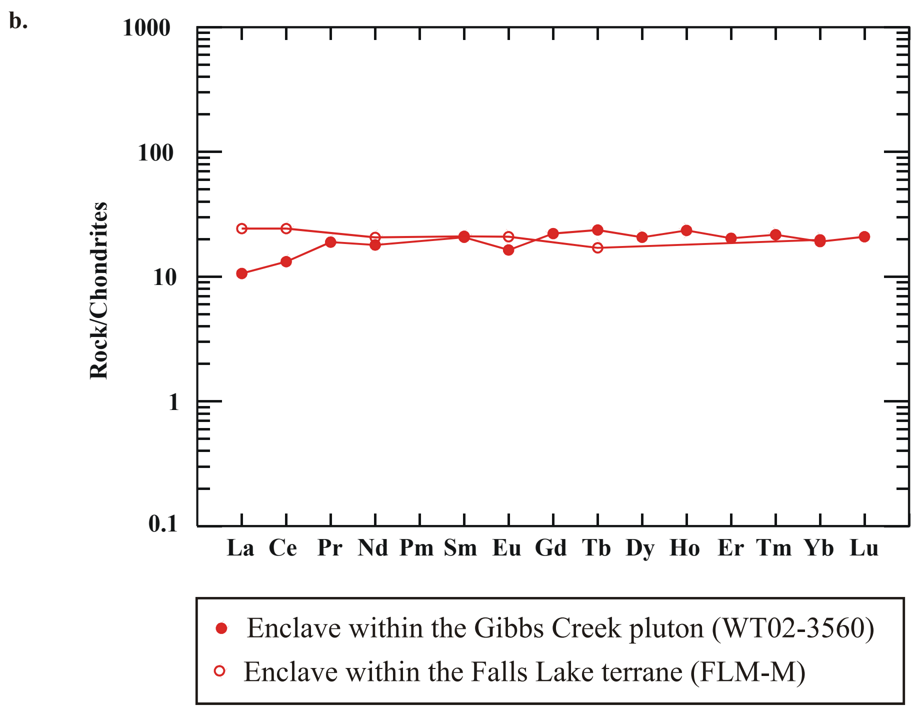


Figure 24: Nakamura (1974) chondrite-normalized REE diagrams for the: a) Gibbs Creek pluton, Middle Creek Gneiss, and Falls Lake terrane matrix samples and the b) enclaves with in the Gibbs Creek pluton and Falls Lake terrane.

resulting in a mix of slight positive to slight negative Eu anomalies suggesting a potential plagioclase fractionation or enrichment in the samples.

The enclave rare earth element data for samples FLM-M and WT02-3560 are reported in Table 3. FLM-M and WT02-3560 are weakly enriched in the LREE (20X chondrite) and overall display a flat trend in the HREE (20X chondrite) (Figure 24b). WT02-3560 is slightly depleted in La and Ce (~10X chondrite). Eu displays a very slight enrichment in FLM-M, but is slightly depleted in WT02-3560. Overall, this REE distribution is typical of mafic igneous rocks displaying a MORB-like signature, but slightly elevated.

Comparison of Geochemical Results

To compare the Carolina terrane rocks within the Tar River area to the rocks within the Falls Lake terrane requires multiple samples from each terrane. Geochemical comparison data was derived from unpublished master's theses of Heller (1996), Phelps (1998), and Grimes (2000), as well as North Carolina Geological Survey STATEMAP geochemical analyses from 1993 to 2002 (Blake and Stoddard, 2004).

From these sources, samples were chosen for geochemical comparison from the easternmost Carolina terrane (Cary sequence) on the southern portion of the western flank of the Wake-Warren anticlinorium. This was done to investigate whether similarities in geochemical signatures exist between the Carolina terrane rocks in the Tar River area and the Carolina terrane rocks to the south, because both terranes contain a greenschist facies metamorphism and a variety of metaigneous rocks. The Carolina terrane samples (Cary sequence) to the south were separated into three groups that included felsic metaplutonic (12 samples: WR92-2, WR92-70, WR94-835, WR94-863, FV98-2645, FV98-2657A, FV98-2657B, FV98-2690, K-291, SLP-1, SLP-5, and SLP-48), mafic metaplutonic (6 samples: CR-3, BD-DI, Wm-1, K-293, Wf-1, and K-290), and felsic to mafic metavolcanic rocks (8 samples, FV98-2724, AP-4, I40QWSC, FV98-2675A, WR92-15 WR93-756, WR92-177, and GLW-79). For the multi-element and REE plots, a gray polygon represents a field for each group of the Carolina terrane samples. For comparison, the samples for this study are superimposed on the gray fields.

On a QAP diagram (Figure 25), the felsic metaplutonic rocks plot within the granodiorite field, the mafic metaplutonic rocks plot within the quartz monzodiorite field. The felsic to mafic metavolcanic rocks show a bimodal distribution, with the more felsic rocks plotting in the granodiorite to granite field and the mafic rocks plot in the gabbro and quartz gabbro field. The felsic metaplutonic rocks show similar mineralogic compositions to the Gibbs Creek pluton samples (Figure 25).

The Sun and McDonough (1989) N-MORB normalized multi-element discrimination diagrams for the three Carolina terrane groups show similarities with one another (Figure 26). All have an enrichment in the LIL elements around 100X N-MORB and a corresponding depletion in the immobile elements. The felsic to mafic metavolcanic group produces a more scattered distribution than the felsic metaplutonic and mafic metaplutonic. Comparing the data of this study with fields generated from the data of the Carolina terrane reveals that all three groups (Figure 26a, b, c) show similar trends with respect to the Gibbs Creek samples.

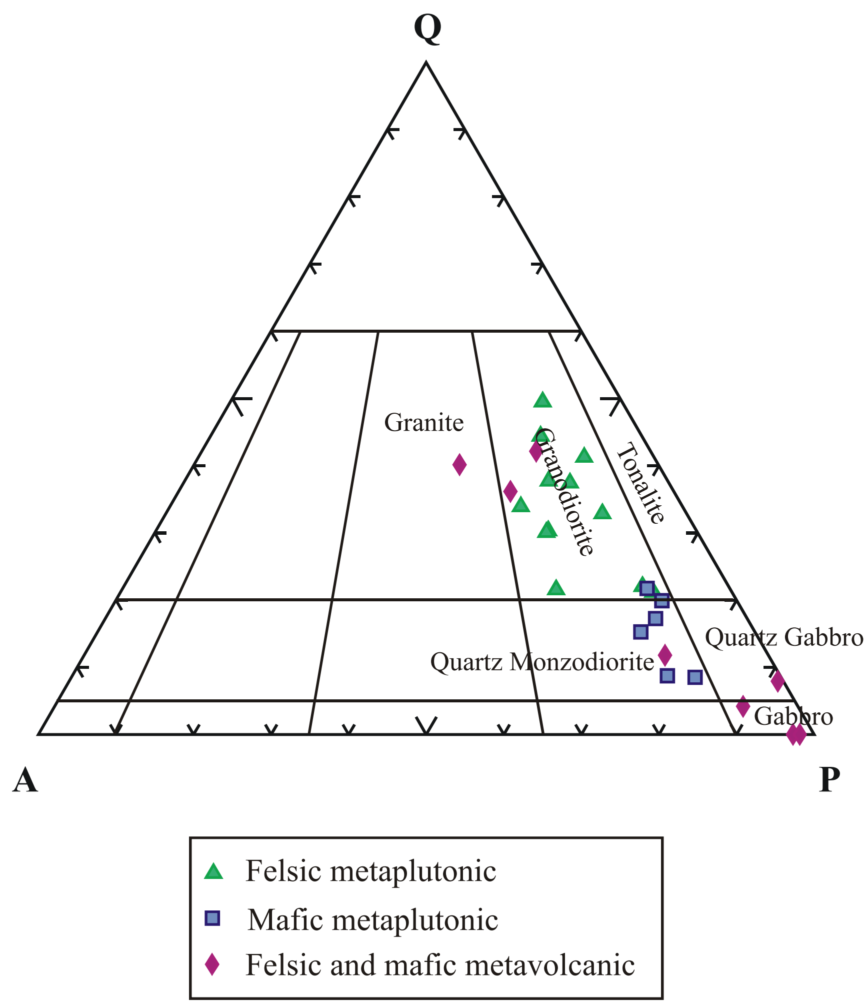


Figure 25: QAP classification diagram for the three easternmost Carolina terrane groups, felsic metaplutonic, mafic metaplutonic, and felsic and mafic metavolcanic.

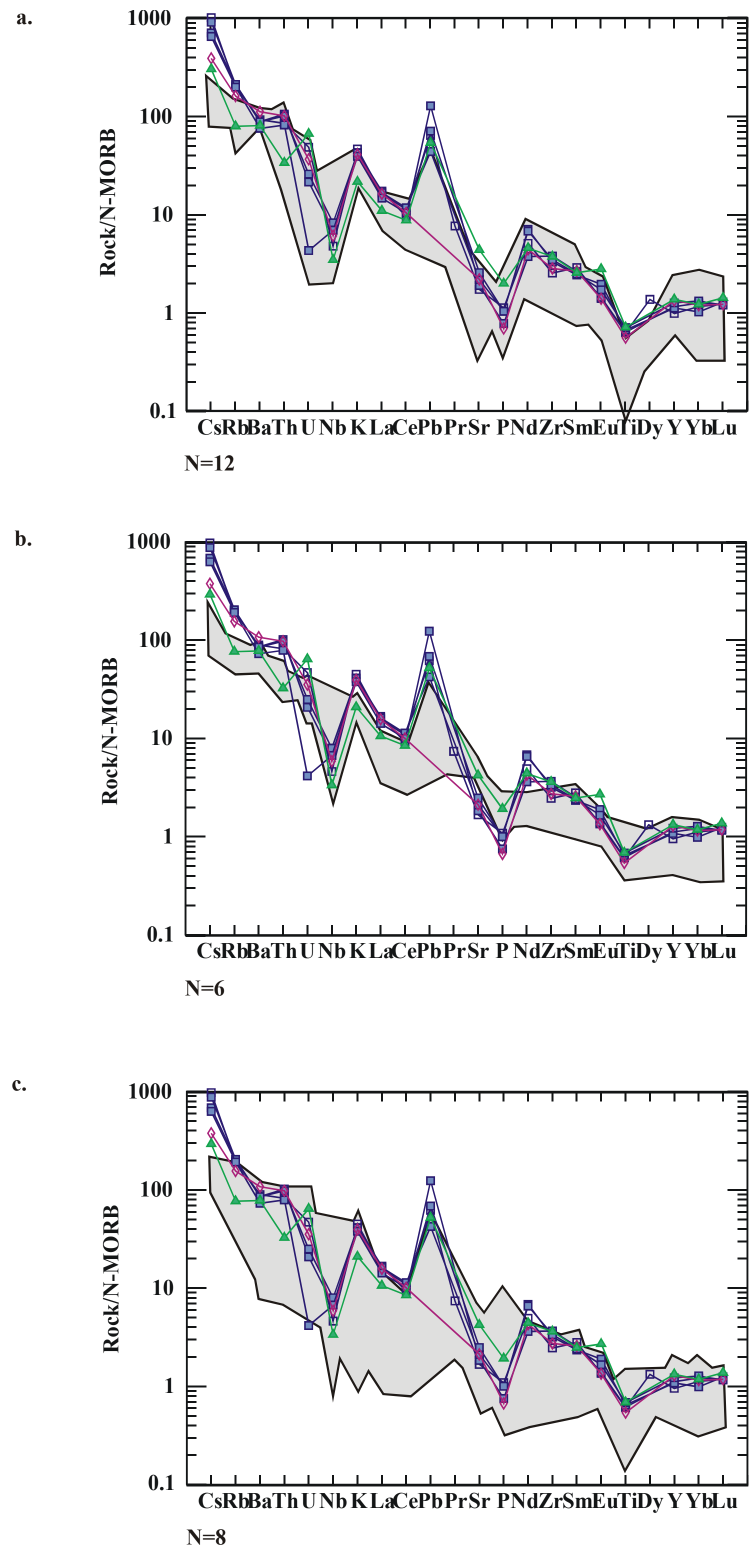


Figure 26: Sun and McDonough (1989) N-MORB-normalized multi-element diagrams for the three easternmost Carolina terrane groups (in gray): a) felsic metaplutonic, b) mafic metaplutonic, and c) felsic and mafic metavolcanic. Samples from this study are superimposed (in color).

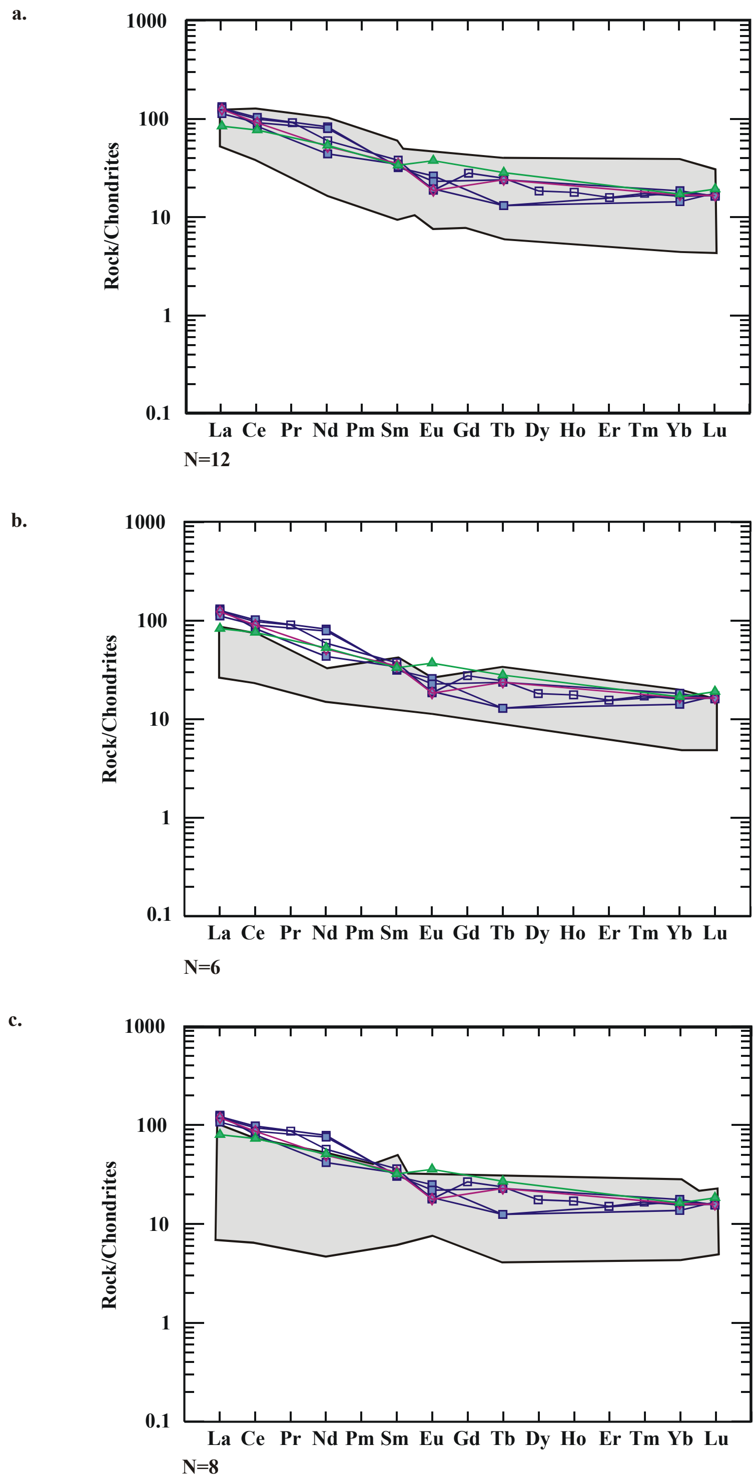


Figure 27: Nakamura (1974) chondrite-normalized REE diagrams for the three easternmost Carolina terrane groups (in gray): a) felsic metaplutonic, b) mafic metaplutonic, and c) felsic and mafic metavolcanic. Samples from this study are superimposed (in color).

The Nakamura (1974) chondrite-normalized REE plots for the three Carolina terrane groups display an enrichment in the LREE (100X chondrite) and display a consistent trend approximately 10 - 50X chondrite in the HREE (Figure 27). Again, the felsic to mafic metavolcanic group displays a more scattered plot, especially in the LREE (10 – 100X chondrite). These REE distributions are also similar to the REE results from the Gibbs Creek pluton.

In conclusion, all rocks samples in this study are inherently part of the Carolina Zone (Hibbard and Samson, 1995; Hibbard and others, 2002) and the data reflects that all are comparable and contain numerous similarities. In the multi-element diagrams, all samples display enriched LIL elements and a depletion in immobile elements. This pattern is indicative of rocks from a volcanic island-arc setting especially troughs in Nb and Ti (Wilson, 1989). Also, the REE diagrams of all the samples display enrichment of LREE and a depleted flat HREE trend that is typical of calc-alkaline rocks within an island-arc setting (Wilson, 1989).

To further investigate the origins of these rocks, two tectonomagmatic discrimination diagrams were generated. The felsic samples on a Rb vs Y+Nb tectonomagmatic discrimination diagram (Pearce and others, 1984) display a volcanic island-arc origin (Figure 28a,b). The Carolina terrane samples do contain some that fall in the “within-plate” category (Figure 28b) that may indicate some continental influence or the samples may be more leucocratic. This will be discussed further in the DISCUSSION CHAPTER. Since the samples have undergone metamorphism, it is important to use elements that are relatively immobile metamorphism. The mafic samples on a (Ti/100)-Zr-(Y*3) tectonomagmatic discrimination diagram (Pearce and

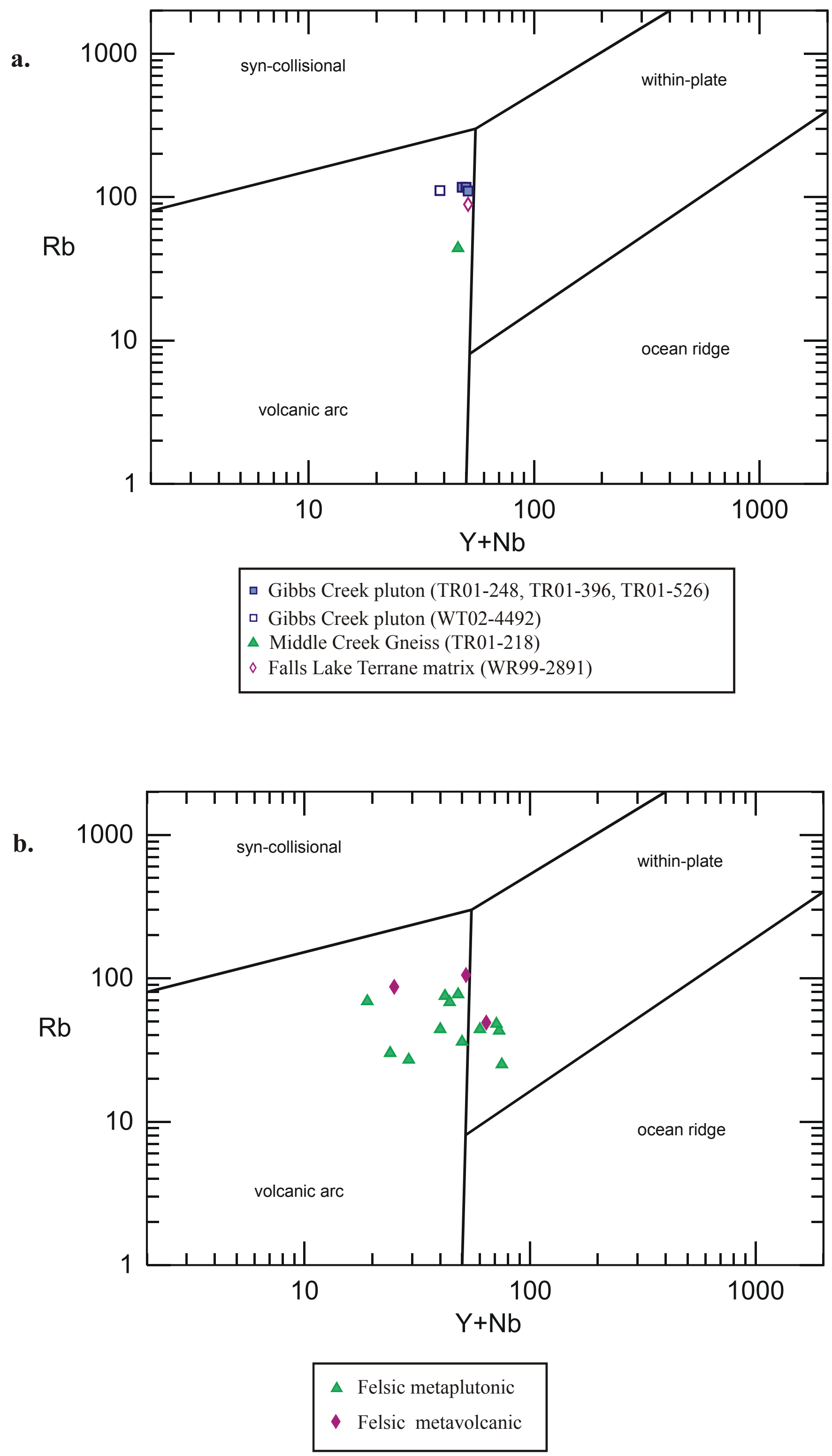
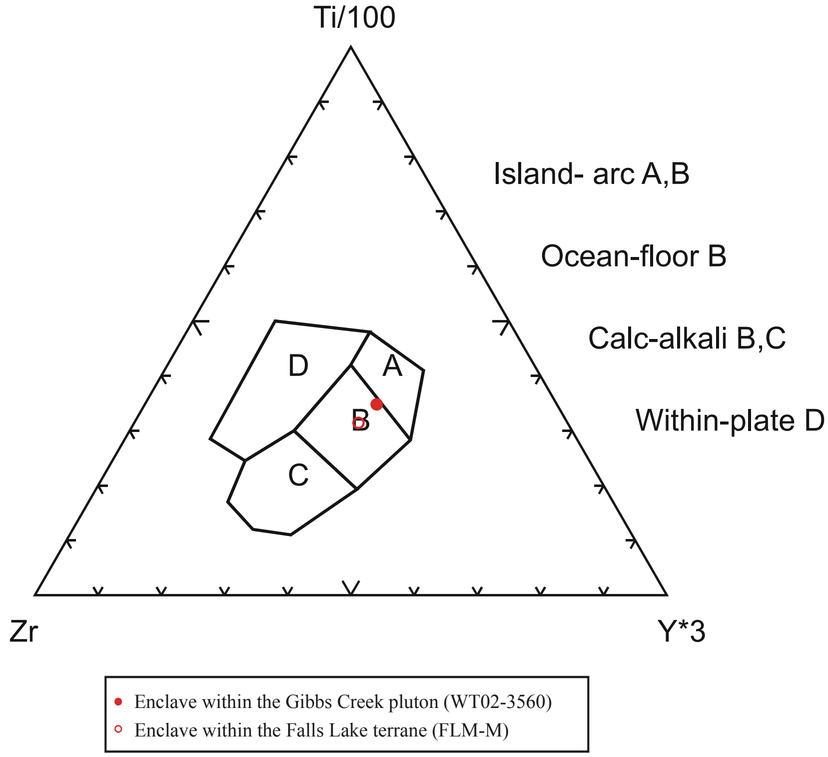


Figure 28: Rb vs Y+Nb tectonomagmatic discrimination diagrams (Pearce and others, 1984) for the a) felsic samples in this study and b) the Carolina terrane felsic samples.

a.



b.

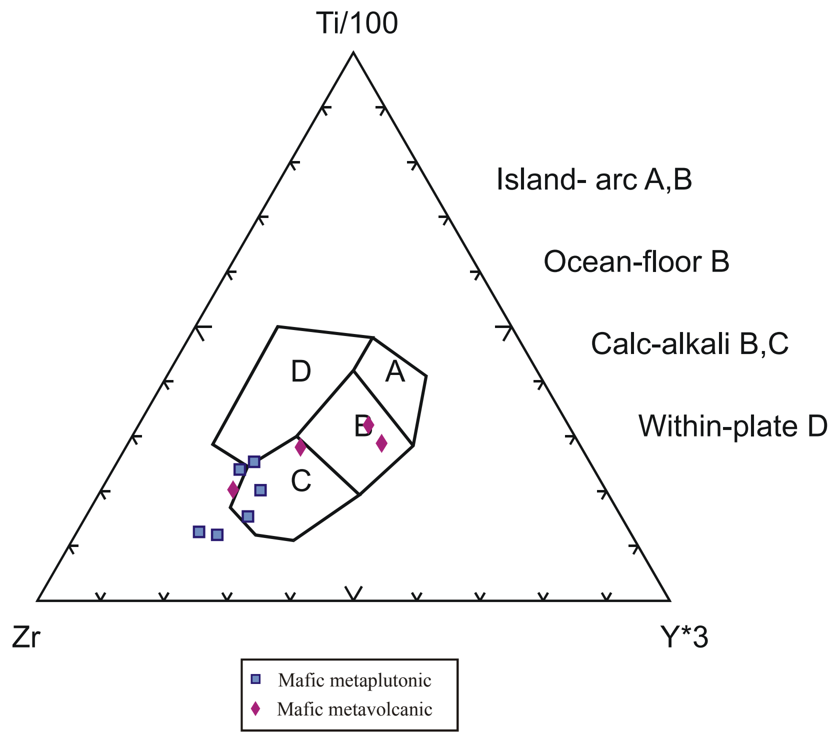


Figure 29: (Ti/100)-Zr-(Y*3) tectonomagmatic discrimination diagrams (Pearce and Cann, 1973) for the a) mafic samples in this study and b) the Carolina terrane mafic samples.

Cann, 1973) indicate a calc-alkaline volcanic island-arc origin (Figure, 29a,b). The enclaves WT02-3560 and FLM-M display an ocean floor MORB signature that may indicate a primitive crust on which the island-arc was built. This will also be discussed further in the DISCUSSION CHAPTER.

All samples appear to be part of a calc-alkaline island-arc known as the Carolina Zone. Based upon field observations, both the Carolina terrane within the Tar River area and the Falls Lake terrane to the south, are of intermediate composition and contain enclaves of metamafic to metaultramafic rock. A silicified ridge separates these two terranes and creates a metamorphic discontinuity between them. The Carolina terrane is at greenschist facies and the Falls Lake terrane is at amphibolite facies. Major element, multi-element, and REE compositions (this study) are similar for the Gibbs Creek pluton samples and the Falls Lake terrane sample. The geochemical data for the enclaves, however, is quite different from the matrix rock, although similarities exist between the two enclaves even though the Moye (1981) data is incomplete.

The rocks on the western flank of the Wake-Warren anticlinorium have been truncated, juxtaposed and folded and have been assigned terrane affinity based on field observations, metamorphic facies, and fault boundaries. This data is not conclusive in determining whether the Carolina and the Falls Lake terranes contain the same rock type at different grades of metamorphism. However, these results suggest that the assignment of terranes on the western flank of the Wake-Warren anticlinorium may need to be re-examined.

STRUCTURE

Introduction

A structural analysis of the Tar River area involved categorizing the macroscale structures and mesoscale to microscale fabric elements observed in all terranes and intrusive bodies. Two different structural analyses, geometric and kinematic, were conducted in an attempt to understand the developmental history among the structures, metamorphism, magmatism, and the tectonic events that affected the area. Results of the geometric and kinematic analyses are summarized into a structural significance of fabric elements, folds, and faults.

Geometric analysis first involved field mapping of lithologic units. This provided orientation data with which to decipher the progressive development of fabric elements and mutual overprinting relationships as well as allowing a determination of the sequential history of structure and fabric element development. Field traverses along creeks and the Tar River provided the best exposure of rocks in the study area. Traverses were also conducted along county, state, and federal roads where rocks are exposed along roadside ditches and cuts.

Orientations of structures were measured using a Brunton compass. Measurements including strike and dip of foliations, axial surfaces, and fracture surfaces, and trend and plunge of lineations and fold hinges were recorded during the traverses. The data were analyzed using the program Stereonet© v. 4.6 by Almendinger on a Macintosh computer.

Kinematic analysis was conducted on structures from fault zones. Hand samples were collected from selected outcrops having structural significance. Both oriented and unoriented thin sections were obtained from these hand samples. Oriented thin sections were cut parallel to lineation and some were cut perpendicular to lineation to reveal the maximum amount of shear sense information. Shear sense indicators are the product of asymmetric structure development as well as composite fabric elements in high strain zones.

To aid in the examination of the structural elements, the Tar River area was separated into two structural domains, Domain I and Domain II (Figure 30). A prominent divider within the Tar River area is the silicified ridge, which marks the distinctive metamorphic facies discontinuity and is used to separate the structural domains. Domain I lies west of the silicified ridge and preserves penetrative fabric elements in discrete zones. Domain II lies east of the silicified ridge and preserves penetrative fabric elements over a broad area.

Geometric Analysis

The structures and fabric elements observed within the Tar River area, in relative age order, are: 1) a compositional layering, S_0, observed within the Type 2 amphibolite enclaves of the Gibbs Creek pluton of the Carolina terrane, and within the macroscale and mesoscale lithologic units; 2) a penetrative foliation, S_e, within the Type 2 and Type 4 foliated metagranitoid enclaves within the Gibbs Creek pluton; 3) a penetrative foliation, S_1, within macroscale and mesoscale lithodemic units that is

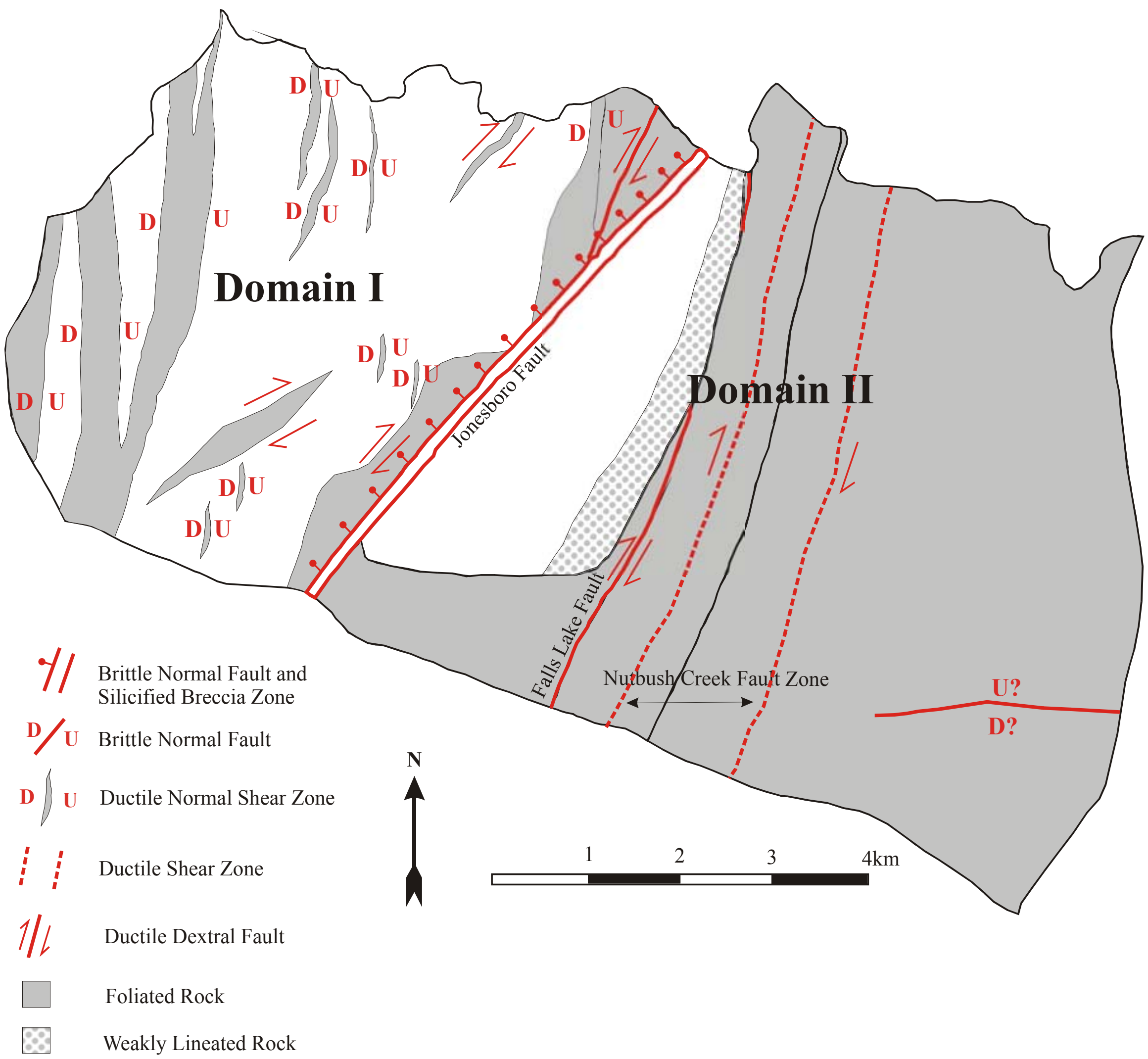


Figure 30: Domain and fault map for the Tar River area. Domain I is the west of the silicified ridge (Jonesboro fault) and Domain II is the area east. The main structures are the Nutbush Creek fault zone, Falls Lake fault, and the Jonesboro fault.

parallel to subparallel to S_0 throughout Domain II, and occurs locally in discrete zones in Domain I; 4) a penetrative strike-parallel mineral stretching lineation, L_1, associated with S_1; 5) mesoscale and microscale folds, F_1; 6) a penetrative foliation, S_2, that occurs within discrete zones within Domain I; 7) penetrative dip-parallel mineral stretching lineation, L_2, associated with S_2; and 8) nonpenetrative fracture surfaces.

Domain I

The oldest fabric elements observed within Domain I are an S_0 compositional layering and an S_e foliation in the enclaves within the Gibbs Creek pluton. The Gibbs Creek pluton locally contains the S_1 and S_2 fabric elements and associated L_1 and L_2 lineations. The Ruin Creek Gneiss displays the S_1 foliation and the associated L_1 lineation. The foliated metagranodiorite just to the west of the Ruin Creek Gneiss contains both S_1 and S_2 fabric elements and the associated L_1 and L_2 lineations. Also, fractures nonpenetratively overprint the Ruin Creek Gneiss, the foliated metagranodiorite, and the Gibbs Creek pluton.

Compositional Layering, S_0

Compositional layering, S_0, is observed within the Type 2 amphibolite enclaves of the Gibbs Creek pluton. Alternating layers of light and dark colored minerals define S_0 (Figure 31a). The lighter minerals include epidote that has partially replaced plagioclase while the mafic minerals include chlorite that has partially replaced hornblende. The compositional layers are continuous in the enclaves, but are truncated at their contact with the Gibbs Creek pluton (Figure 31a).

a.

b.

Figure 31: a) Outcrop photograph of S_0 and S_e in the amphibolite enclaves. Rock hammer (27 cm long) for scale. b) Outcrop photograph of S_e in a metagranitoid enclave. Scale bar is 15.24 cm long.

Tectonite Fabric

Two different types of S_e foliations occur within the Gibbs Creek pluton enclaves: 1) a well-developed planar foliation that overprints S_0 in the Type 2 amphibolite enclaves, and 2) a convoluted foliation that occurs in the Type 4 metagranitoid enclaves. The S_e fabric within the Type 2 amphibolite enclaves is a well-developed planar foliation, oriented subparallel with the S_0 compositional layers (Figure 31a). S_e overprinted the S_0 alternating layers of hornblende and chlorite versus plagioclase and epidote. The hornblende and chlorite display a subparallel mineral alignment between crystalloblastic layers of sausseritized plagioclase. The S_e fabric is truncated at the edges of the amphibolite enclaves and is in sharp contact with the nonfoliated Gibbs Creek pluton.

The S_e foliation of the Type 4 metagranitoid enclaves appears convoluted in the mesoscale, which is quite different from the S_e foliation of the Type 2 amphibolite enclaves (Figure 31b). Aligned chlorite and biotite plates occur between quartz and plagioclase, which define the S_e foliation in the metagranitoid enclaves. The S_e has a convoluted orientation and commonly contains folded or tightly appressed phyllosilicate layers. Locally, this convoluted foliation wraps around the Type 1 greenstone and Type 2 amphibolite enclaves. The S_e fabric is truncated at the contact with the nonfoliated Gibbs Creek pluton. Orientations were gathered from Type 4 metagranitoid enclaves. The orientations of this convoluted S_e foliation are scattered, but there is a weak preferred orientation that trends toward N25E to N35E (Figure 32).

A penetrative S_1 foliation occurs within the Ruin Creek Gneiss, metagranodiorite, and discrete zones within the Gibbs Creek pluton. S_1 within the Ruin Creek Gneiss contains granoblastic, dynamically recrystallized quartz, microcline, and

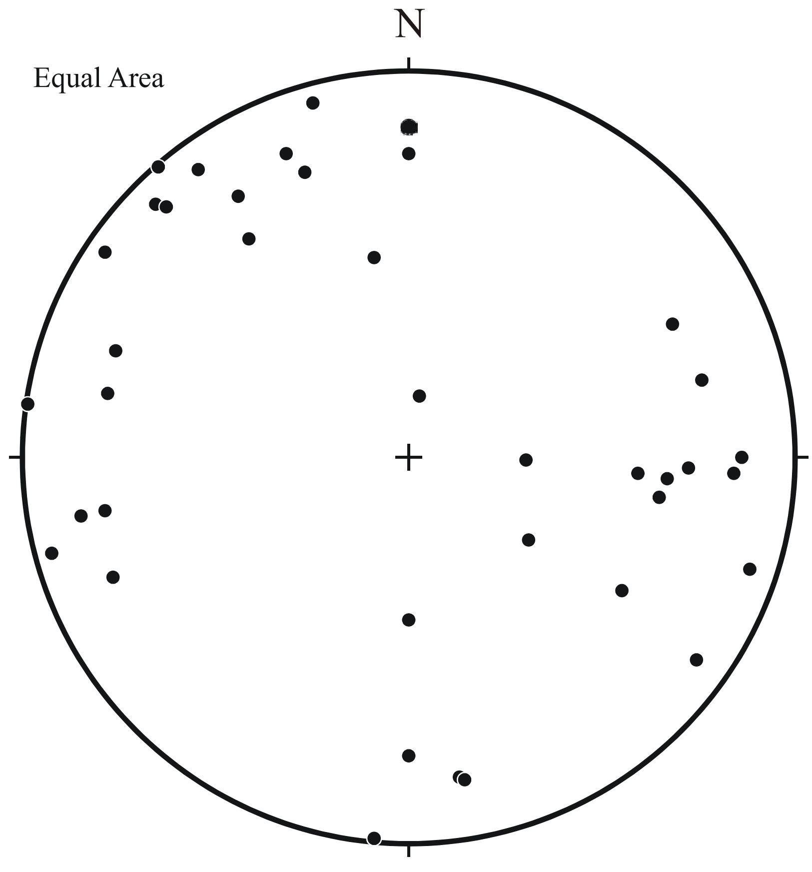


Figure 32: Stereographic display of orientations of the S_e foliation in the metagranitoid enclaves within Domain I. Orientations are dispersed, but show a general N20E to N40E strike and a moderate to steep NW and SE dips. (n=39 poles to strike)

plagioclase, and minor amounts of aligned chlorite and white mica plates. Together, these minerals produce a mylonitic fabric. The Ruin Creek Gneiss also contains sigma-type porphyroclasts of microcline that display chlorite, white mica, and recrystallized quartz wings. Within the metagranodiorite, aligned chlorite and white mica plates, along with quartz, pyrite, and epidote porphyroclasts define a mylonitic S_1 foliation. S_1 in the discrete zones within the Gibbs Creek pluton contains chlorite and white mica plates that are aligned in thin parallel layers associated with dynamically recrystallized microcline, plagioclase, and quartz. S_1 within these discrete zones forms a mylonitic fabric. When abundant chlorite and lesser amounts of white mica are aligned in these planar layers, the S_1 foliation forms phyllonite zones in the Gibbs Creek pluton. Commonly within these zones, the porphyroclasts are epidote, pyrite, single undulatory quartz crystals, polycrystalline quartz subgrains, or chlorite "fish". The S_1 foliation within these zones has a N25E to N35E strike and is steeply dipping (Figure 33).

S_1 is associated with a mineral stretching lineation L_1 that lies within the foliation plane of S_1. Recrystallized quartz, quartz ribbons, and phyllosilicate alignment define L_1. L_1 is a subhorizontal lineation that has a shallow 7º to 17º plunge to the northeast (Figure 33). F_1 folds are tight- to open-style similar folds that occur fold S_1. The axial surface of these folds occur ~30° to 40° from the foliation of S_1. F_1 folds plunge steeply and most likely formed late syn-tectonic within the S_1 foliation.

An S_2 foliation occurs as discrete zones within Domain I predominately on its west side. These discrete zones are located within the Gibbs Creek pluton and have a penetrative phyllonitic foliation. The S_2 fabric contains layers of predominately chlorite and some white mica with chlorite "fish" and plagioclase porphryoclasts.

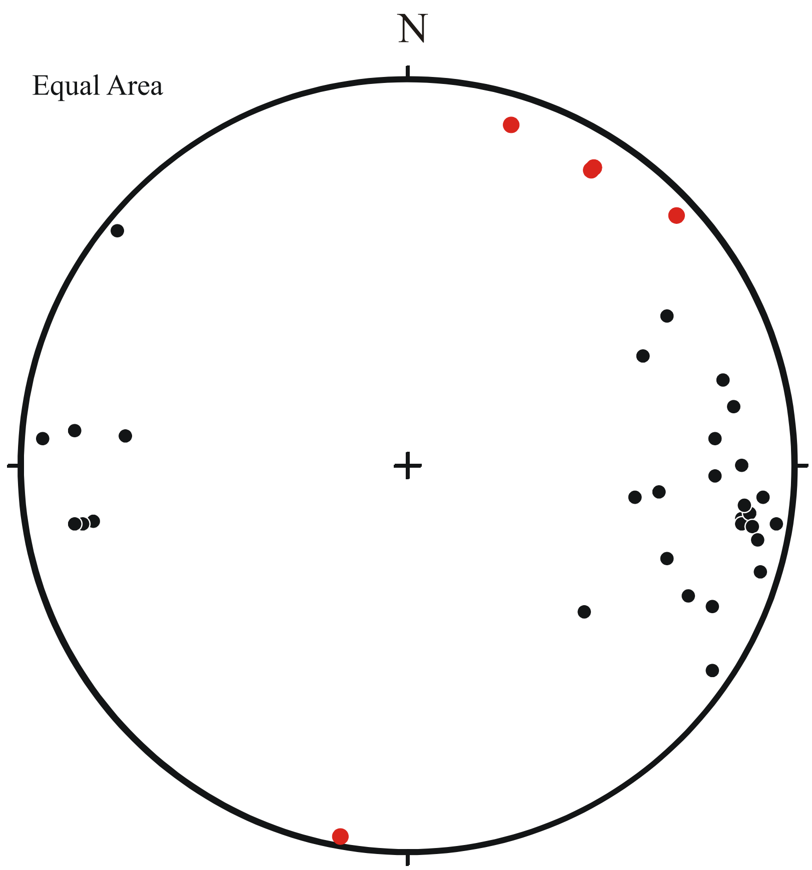


Figure 33: S_1 foliation pole orientations within Domain I (Black circles, n=30). The stereographic display demonstrates that the foliation has a N15E to N25E strike and a steep dip. L_1 lineation (Red circles, n=5) have a shallow plunge that is subparallel with the S_1 foliation.

S_2 foliations have a similar strike orientation (N10E to N25E) as the S_1 foliations (Figure 34), but differ in their lineation. The S_2 foliation contains a mineral stretching lineation, L_2, that has a subvertical plunge towards the west (Figure 34). Chlorite and white mica define the mineral stretching lineation. L_2 can be gradational between a penetrative lineation to nonpenetrative slickenlines and vein fibers on the S_2 foliation plane.

Silicified Ridge

A semi-linear silicified ridge cuts the Tar River area into its two domains. Along this ridge, higher peaks are composed of multiply-fractured, silicified breccia. In thin section, fractures cut large quartz crystals. Also, brecciated quartz occurs with recrystallized quartz as the matrix between larger unfractured and fractured crystals (Figure 11a). At lower elevations between ridges, brecciated pieces of Carolina terrane rock such as greenstone are silicified, and vuggy quartz occurs at the triple points among the brecciated pieces (Figure 11b). Fractures related to the silicified ridge are observed within the adjacent mylonites of the Ruin Creek Gneiss and the Gibbs Creek pluton to the west.

These fractures occasionally crosscut and non-penetratively overprint the S_1 and S_2 foliation (Figure 35a). The fractures contain epidote and/or quartz crystals, and in some cases drag folds are created when fractures cut the ductile foliation (Figure 35b). Within the S_1 and S_2 foliation plane, some plagioclase porphyroclasts develop kink bands and microfaults between cleavage planes (Figure 36a, b), which indicates ductile-brittle deformation. Zones of cataclastic material occur parallel with the S_1 and S_2 foliations (Figure 37). In addition, zones of cataclastic to ultracataclasite material form

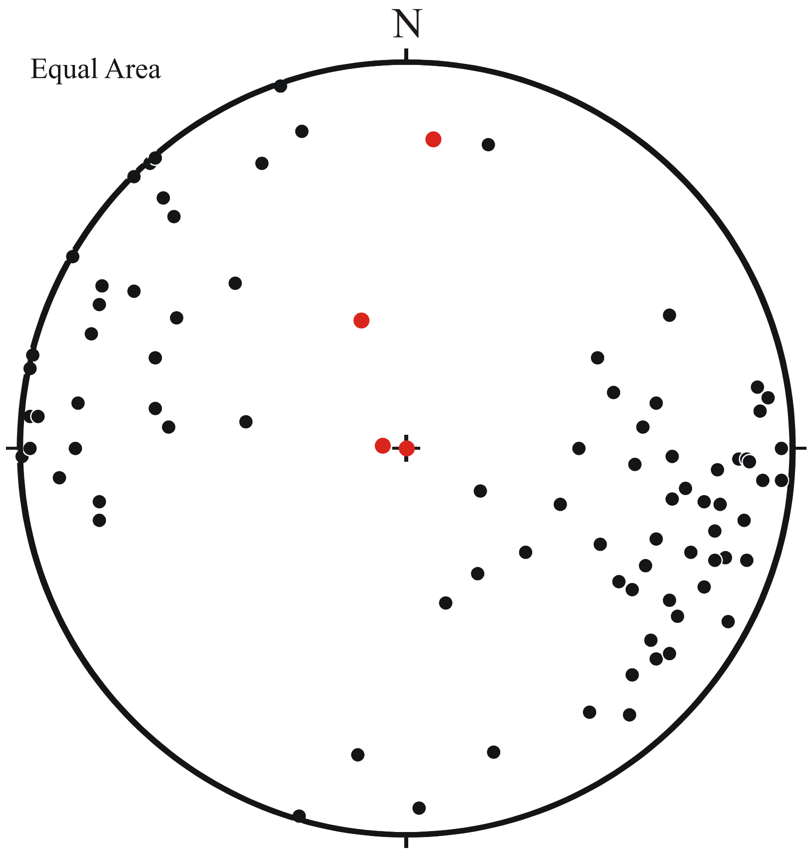
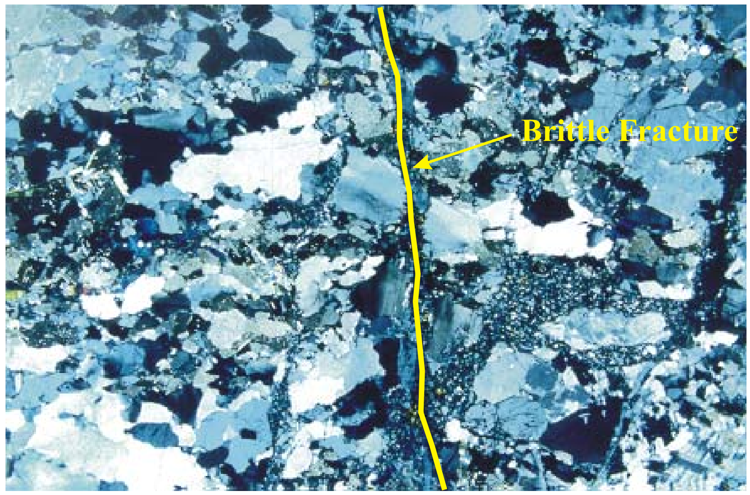


Figure 34: S_2 foliation pole orientations within Domain I (Black circles, n=83). The stereographic display demonstrates that the foliation has a N20E to N30E strike and a moderate to steep dip. L_1 lineations (Red circles, n=4) have a subhorizontal plunge within the S_2 foliation.

a.



b.

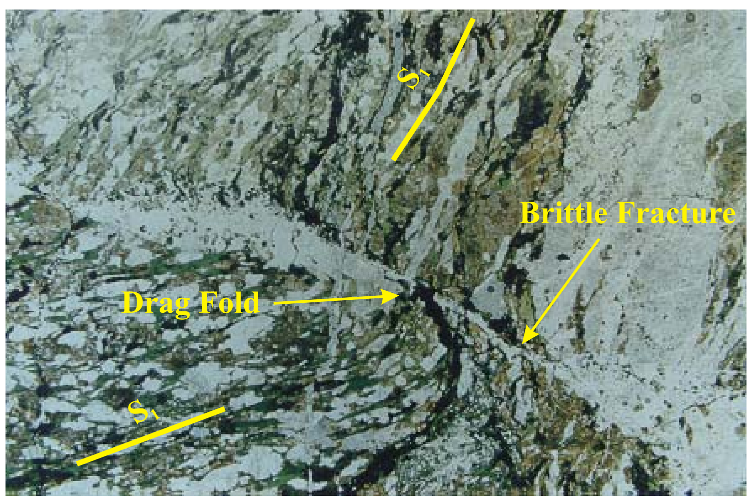
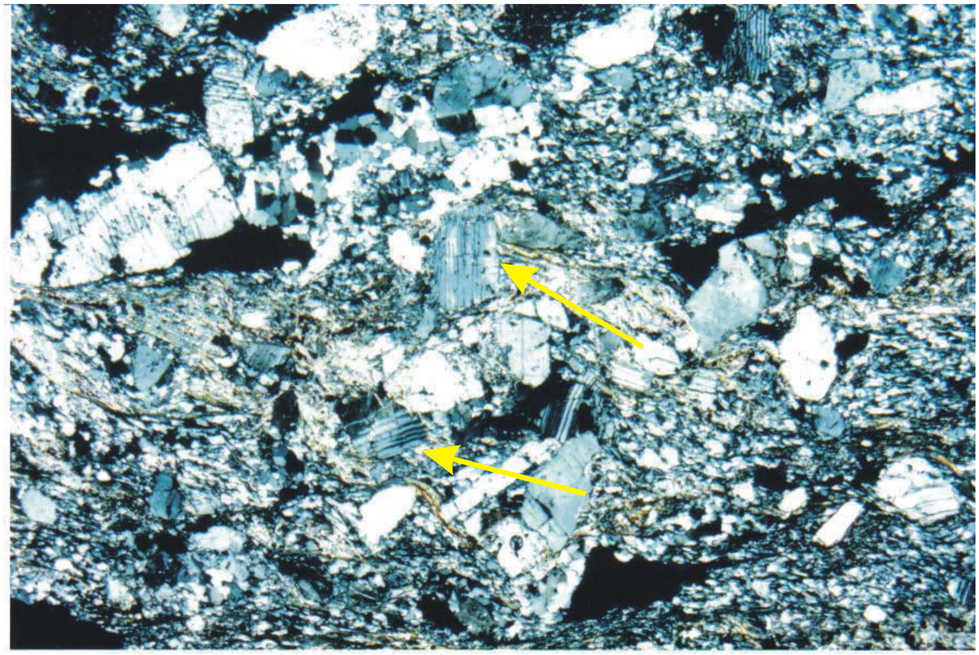


Figure 35: a) Photomicrograph of a brittle fracture that crosscuts the ductile S_1 foliation. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm. b) Photograph of a brittle fracture that crosscuts the ductile S_1 foliation and produced a drag fold. Plane-polarized light. Magnification 1.25X. Field of view is 1.7 cm.

a.



b.

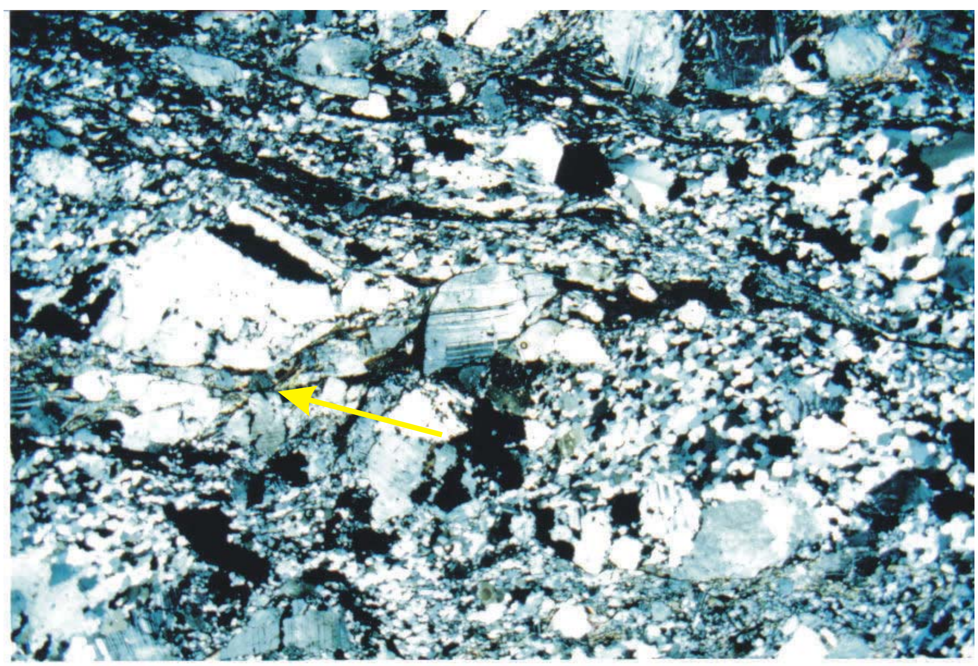


Figure 36: a) and b) Photomicrographs of ductile-brittle structures in the S_1 and S_2 foliations. Plagioclase contains microfaults and kink folded polysynthetic twinning. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm.

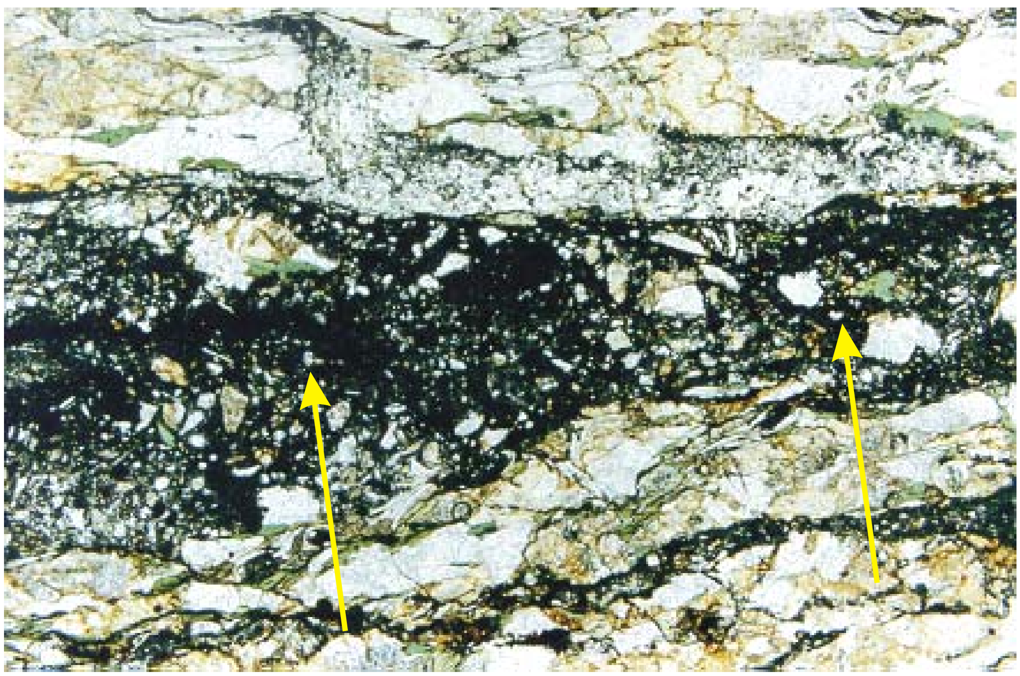


Figure 37: Photomicrograph shows a zone of cataclasite to ultracataclasite. Plane – polarized light. Magnification 1.25X. Field of view is 1.7 cm.

subparallel to the S_2 foliation and contain angular fragments of quartz and chlorite crystals within a fine-grained matrix of epidote. In the Tar River area, the silicified ridge strikes approximately N30E to N40E and contains multiple sets of joints and fractures that overprint the silicified knobs on the topographic highs (Figure 38).

Domain II

Domain II lies east of the silicified ridge (Figure 30) and comprises the following rock units: the Wilton pluton, Falls Lake Schist of the Falls Lake terrane, the Middle Creek Gneiss of the Crabtree terrane, and the Falls Leucogneiss, Raleigh Gneiss, and granitoids of the Raleigh terrane. The oldest fabric preserved in Domain II is a compositional layering, S_0. A regional S_1 foliation is superimposed over all the units within Domain II. The Wilton pluton displays a weak linear mineral alignment related to S_1 along its eastern boundary. An L_1 stretching lineation lies within S_1. Small-scale F_1 folds were observed within Domain II. These small folds occur within the Middle Creek Gneiss. An east-west trending brittle fracture also crosscuts the Raleigh terrane.

Compositional Layering, S_0

S_0 is a compositional layering that occurs on the macroscale and mesoscale. Layers can range from several cm to tens of m in thickness. The Raleigh Gneiss, Falls Leucogneiss, Middle Creek Gneiss, and Falls Lake Schist are lithodemes representing macroscale layers. Lithodemes such as the Raleigh Gneiss and the Middle Creek Gneiss are compositionally interlayered on the mesoscale as well, but the layering tends to be more discontinuous. The layers range from felsic, intermediate, and mafic in

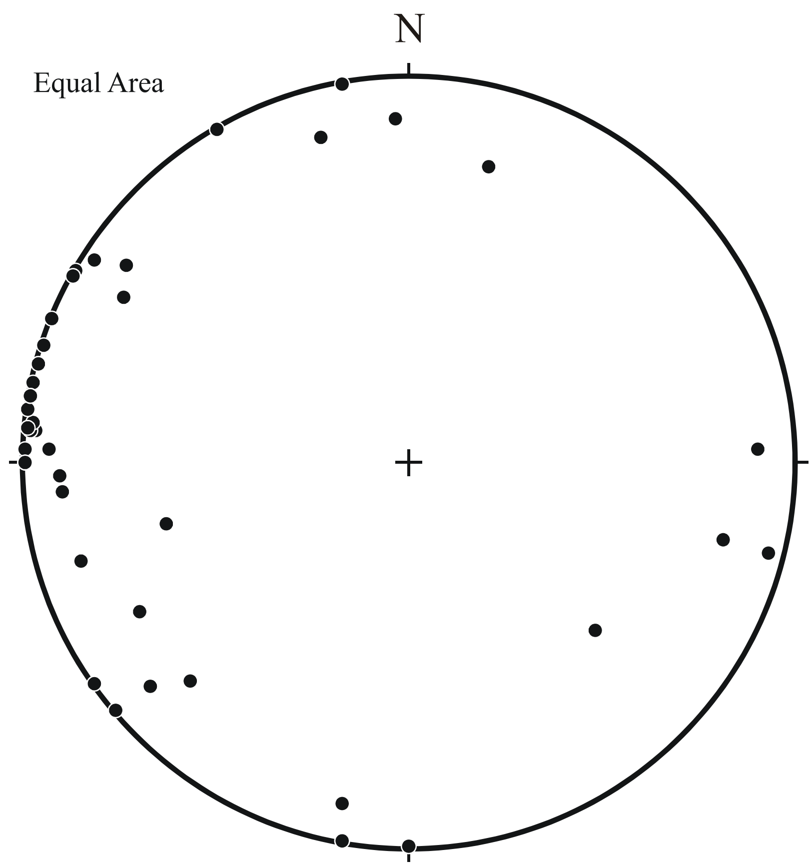


Figure 38: Stereographic display of fracture surfaces within the silicified breccia. A dominant fracture strike is approximately N30E to N40E. Most dips are nearly subvertical to vertical. (n=44 poles to strike)

composition and include local blocks of ultramafic rocks. The felsic layers contain crystalloblastic quartz, plagioclase, microcline, white mica, with minor amounts of biotite. Intermediate layers contain the same mineralogy as the felsic layers, but contain more biotite. The mafic layers contain crystalloblastic plagioclase and nematoblastic hornblende. The metaultramafic rocks form discontinuous pods within mainly mafic rocks and are composed of actinolite, chlorite, and talc.

Tectonite Fabric

S_1 overprints all lithologic units east of the silicified ridge in the Falls Lake, Crabtree, and Raleigh terranes. The Wilton pluton displays signs of L_1 along its eastern boundary. S_1 is a well-developed, penetrative regional foliation that overprints the mineralogic layering S_0. The foliation can range from a schistosity to a gneissosity depending upon the phyllosilicate content, but is predominately the latter. S_1 is a schistosity in the Falls Lake terrane where the foliation consists mainly of white mica plates with minor amounts of biotite plates aligned between layers of recrystallized quartz and plagioclase. Garnet porphryoblasts also occur within this biotite white mica schist. The gneissic S_1 foliation in the felsic and intermediate units of the Crabtree and Raleigh terranes contains a parallel to subparallel alignment of biotite, chlorite, and white mica plates and crystalloblastic layers of quartz and plagioclase and/or microcline. In mafic or amphibolitic units, hornblende prisms are nematoblastic and aligned in a subhorizontal stretch direction between crystalloblastic plagioclase layers. Orientations of the S_1 foliation have a N10E to N20E strike and are steeply dipping to the SE and NW (Figure

39). S_1 is not observed within the metaultramafic rocks, as they are generally massive.

Grain size reduction increases in the S_1 foliation near the contact with Falls Leucogneiss. S_1 in the Falls Leucogneiss occurs as recrystallized gneissic layers of quartz and microcline. The Falls Leucogneiss has a distinctive N15E strike (Figure 40). The Falls Leucogneiss acts as a more competent layer and has a larger grain size than the units to the immediate west and east. However, L_1 is more pervasive within the Falls Leucogneiss and the lithodemes is primarily an L>S tectonite.

L_1 is a mineral stretching lineation. In the Falls Leucogneiss, L_1 is a dominate mineral alignment and stretching or rodding lineation that trends along strike with a 3º to 20º plunge to the north or south (Figure 40). Microcline and quartz rods and magnetite minerals define the stretch lineation. In the Falls Lake Schist, Middle Creek Gneiss, and Raleigh Gneiss, this lineation is best observed in the alignment of phyllosilicate minerals such as biotite and white mica. L_1 occurs in the foliation plane of S_1 and has a shallow plunge to the NE and SW (Figure 39).

Minor mesoscale F_1 folds, fold the S_1 fabric and were observed within the Falls Lake, Crabtree, and Raleigh terranes. F_1 folds are multilayer, tight- to open-style similar folds that have steep plunges to the N and S. The axial surface of these folds develop approximately 30° to 40° from the foliation (Figure 41). Within the Middle Creek Amphibolite in the Crabtree terrane, ptygmatic, cuspate-lobate folds were observed. These multilayered folds are a product of the competence contrast that develops between hornblende- and plagioclase-rich layers.

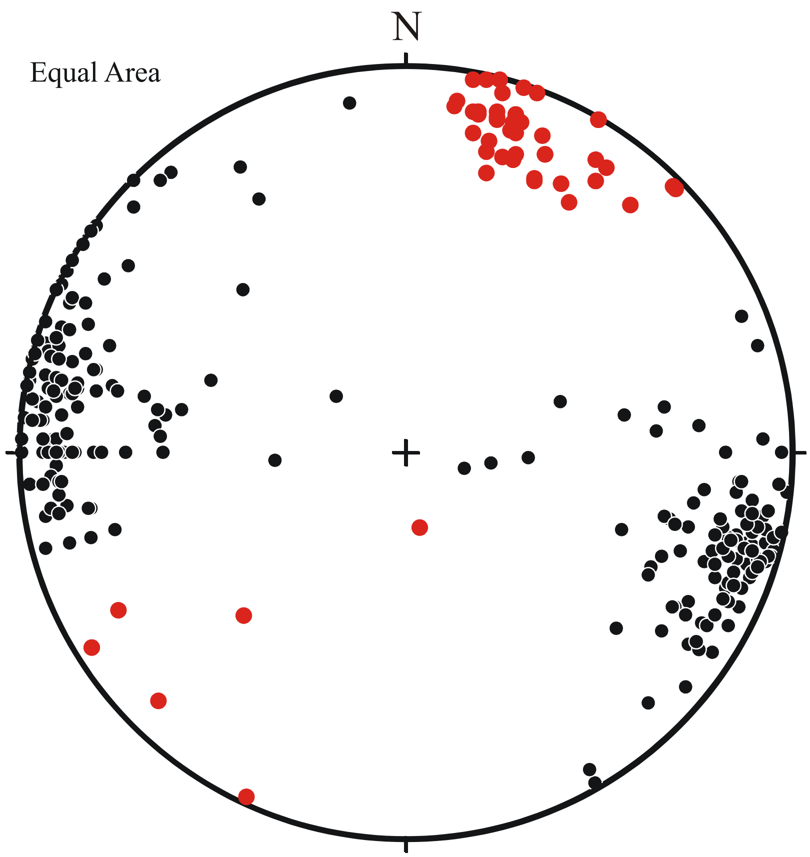


Figure 39: Stereographic display of poles to the S_1 foliation in Domain II. Orientation of S_1 (Black circles, n=241) display a N15E to N20E strike and a moderate to subvertical dip. L_1 is subparallel to strike and contains a relatively shallow plunge (Red circles, n=51).

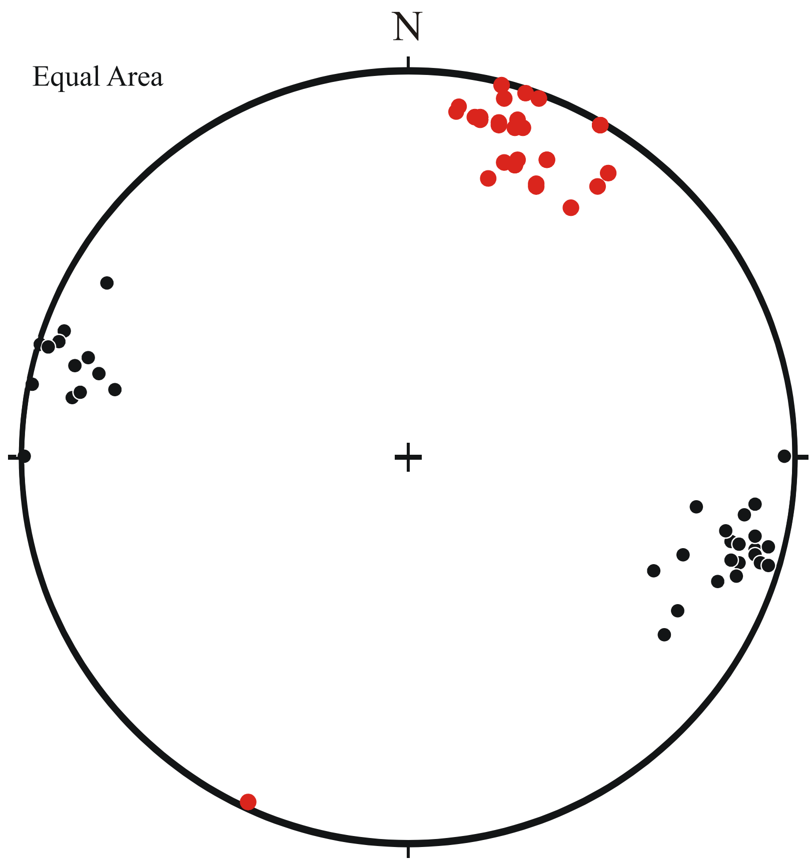


Figure 40: Stereographic display of poles to the S_1 foliation (Black circles, n=38) and L_1 (Red circles, n=31) within the Falls Leucogneiss. The S_1 foliation contains a steep dip and L_1 has a shallow plunge.

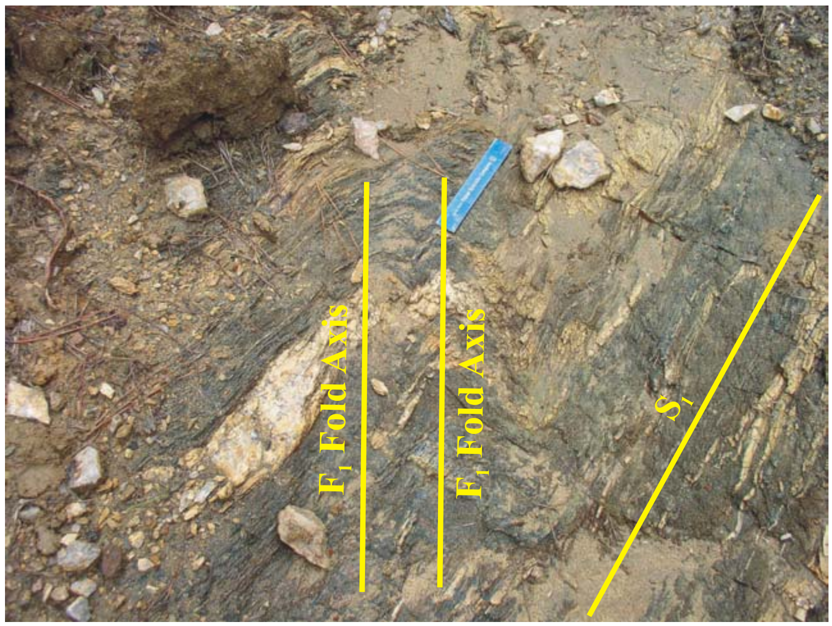


Figure 41: F_1 folds within the Middle Creek Gneiss. The fold hinges occur 30° to 40° from the S_1 foliation. Dark layers are amphibolite with a folded granitoid layer in between. Scale bar is 15.24 cm long.

An east-west trending fault occurs within the Raleigh terrane north of NC 56 and west of US 1. Along this fracture are silicified breccia and silica boulder outcrops help to define this fault zone.

Kinematic Analysis

A kinematic analysis of the Tar River area provides information about the displacements of minerals that are reflected by the development of the geometric fabric elements. These displaced particles are the product of a variety of strains. This kinematic analysis describes the potential displacement histories within Domain I and Domain II.

Domain I

Kinematic indicators were observed in association with the development of the S_1 and S_2 foliations. These occur within the S_1 foliation within the Ruin Creek Gneiss and high strain zones within the Gibbs Creek pluton. The kinematic indicators within the S_2 foliation occur in the high strain zones within the Gibbs Creek pluton.

Kinematic Indicators within the S_1 Fabric

The Ruin Creek Gneiss is a mylonite that contains distinct winged microcline porphyroclasts. In thin section, these porphyroclasts display sigma-type wings that show tops-to-the-north sense of displacement in a vertical to steeply west-dipping gneissic foliation. Porphyroclast wings contain recrystallized chlorite, white mica, quartz, microcline, and plagioclase. Recrystallized quartz ribbons and aggregates of microcline and plagioclase are oriented parallel with the S_1 foliation and define the subhorizontal L_1 lineation. The overall shear sense is dextral within this mylonite.

The mylonite and phyllonite of the Gibbs Creek pluton contain winged porphyroclasts of quartz, epidote, polycrystalline quartz, and pyrite with recrystallized chlorite and quartz wings (Figure 42a, b). Within oriented thin sections, the sigma-type tails display tops-to-the-north or dextral shear sense in a subvertical to steeply west-dipping foliation. Some of the phyllonites contain an S-C fabric (Figure 43). Aligned chlorite and white mica plates along with recrystallized quartz, microcline, and plagioclase define the subhorizontal L_1 lineation. Shear sense indicators show that the overall movement is dextral.

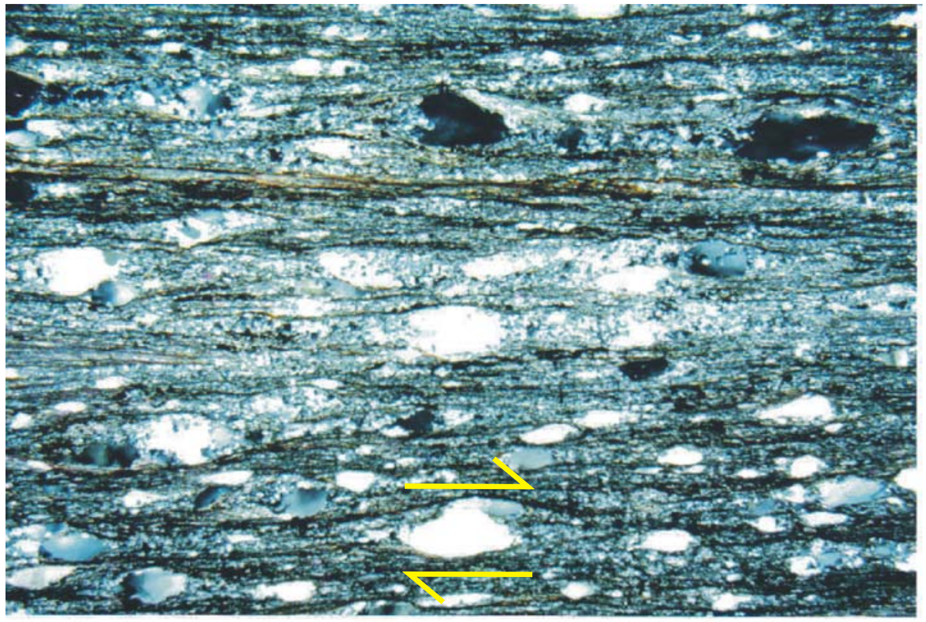
Kinematic Indicators within the S_2 Fabric

The phyllonite containing the S_2 foliation displays chlorite and white mica "fish" along with winged quartz and plagioclase porphyroclasts. Chlorite, white mica, and recrystallized quartz define sigma-type wings. These winged porphyroclasts show a tops-down to-the-west sense of displacement (Figure 44). The tops-down porphyroclast wings and chlorite mineral alignment define a vertical to subvertical down-dip lineation, L_2.

Domain II

Kinematic indicators occur within the S_1 foliation of Domain II. These indicators are more prominent at the boundaries between the Falls Lake, Crabtree, and Raleigh terranes.

a.



b.

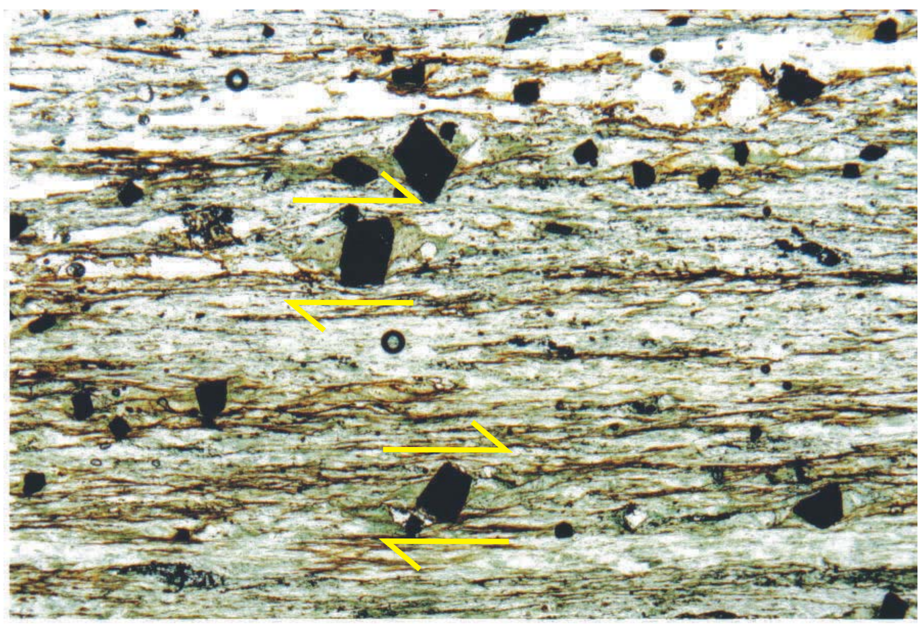


Figure 42: a) Photomicrograph of a dextral quartz porphyroclast with recrystallized quartz wings. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm. b) Photomicrograph of a dextral pyrite porphyroclast with chlorite wings. Plane-polarized light. Magnification 1.25X. Field of view is 1.7 cm.

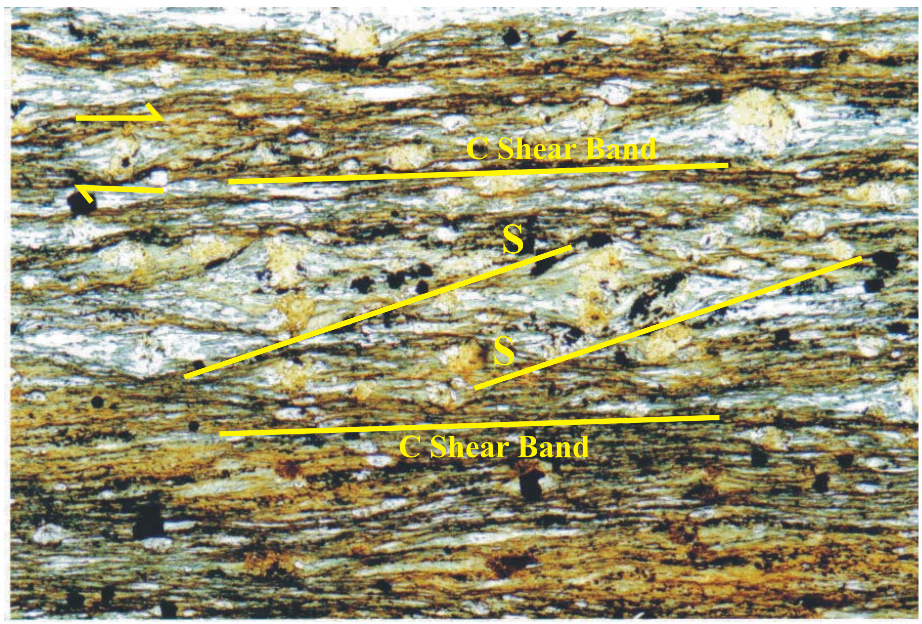


Figure 43: Photomicrograph of an S-C fabric within the S_1 foliation. Dextral porphyroclasts are epidote, pyrite, and quartz with chlorite wings. Plane-polarized light. Magnification 1.25X. Field of view is 1.7 cm.

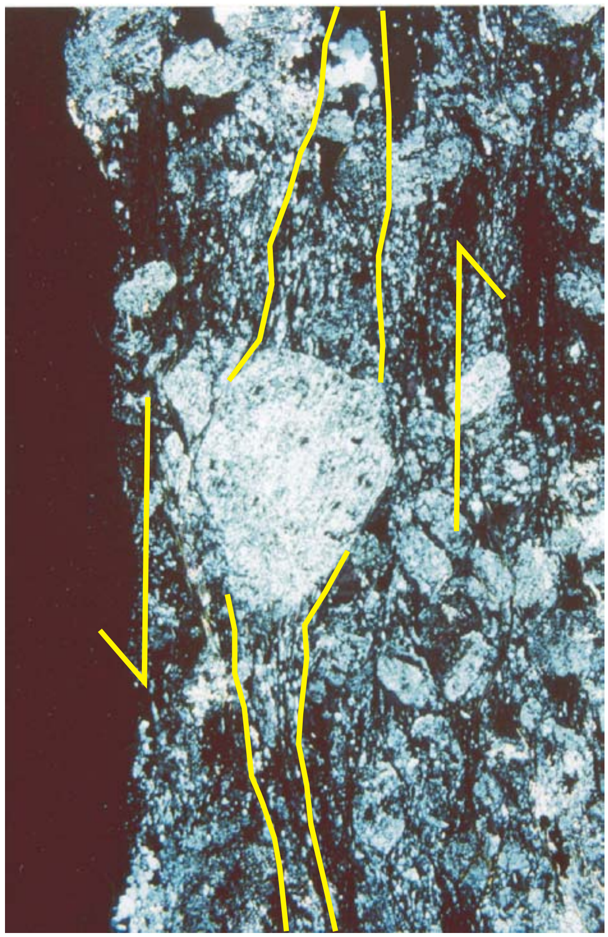


Figure 44: Photomicrograph of a winged feldspar porphyroclast within the S_2 foliation in Domain II. Chlorite and recrystallized quartz wings indicates tops-down-to-the-west. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm.

Kinematic Indicators within the S_1 Fabric

Kinematic indicators within the S_1 foliation occur in the Falls Lake, Crabtree, and Raleigh terranes. Within these terranes, biotite and white mica “fish” display stair stepping, tops-to-the-north or dextral shear sense (Figure 45). Dynamically recrystallized quartz, microcline, and plagioclase within the S_1 foliation do not yield any kinematic indicators in the generally fine grained granoblastic compositional layering.

The subparallel L_1 mineral stretching lineation is a product of the alignment of mica plates or nematoblastic hornblende. L_1 is very prominent within the Falls Leucogneiss. The Falls Leucogneiss is dominated by the L_1 lineation and is an L>S tectonite. All minerals are dynamically recrystallized in the stretch direction. Distinctive indicators for the Falls Leucogneiss are the stretched magnetite crystals.

Structural Significance

Some of the fabric elements and kinematic indicators described for Domains I and II exposed along several fault zones within the Tar River area. These faults are described according to the domains in which they lie.

Domain I

The Ruin Creek Gneiss, metagranodiorite, and the discrete high strain zones within Gibbs Creek pluton contain the S_1 foliation and the L_1 lineation (Figure 30). The Ruin Creek Gneiss is a mylonite and the discrete high strain zones in the Gibbs Creek pluton are mylonite and phyllonite. Kinematic indicators within these S_1 foliations display dextral asymmetry. These mylonites and phyllonites are ductile dextral faults and

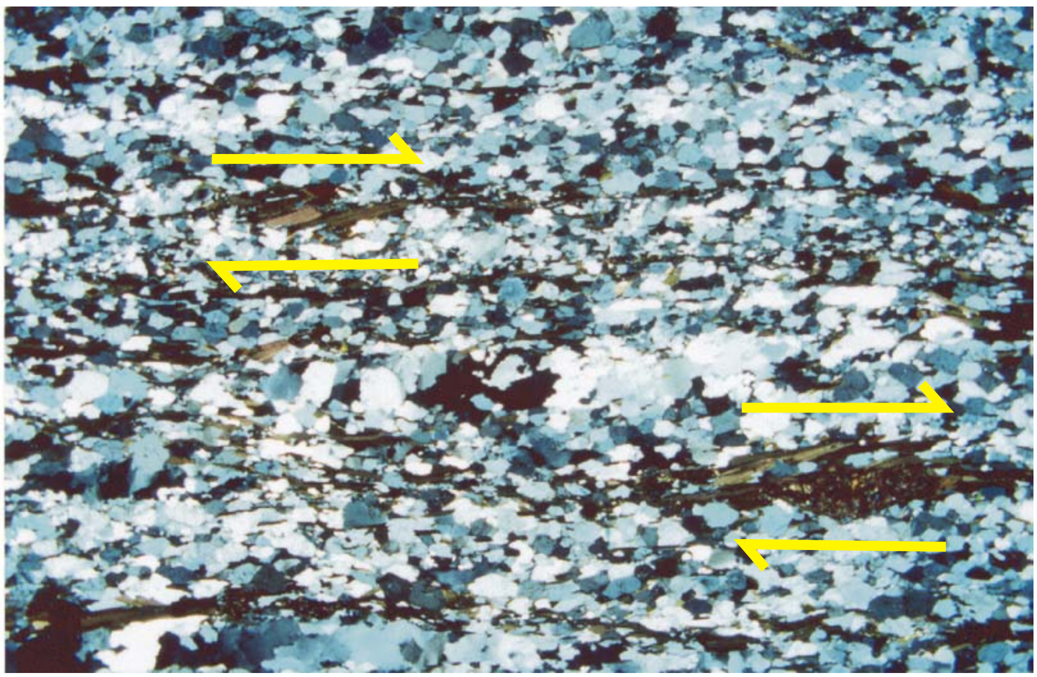


Figure 45: Photomicrograph of biotite plates in a rock from the Middle Creek Gneiss displaying tops-to-the-north or dextral shear sense. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm.

occur mainly in the eastern half of Domain I. These faults are steeply dipping and strike approximately N20E to N30E. Mylonite of the Ruin Creek Gneiss marks the Carolina terrane-Crabtree terrane boundary and this fault is currently unnamed.

The discrete high strain zones containing the S_2 foliation that occurs in the Gibbs Creek pluton are phyllonites (Figure 30). The S_2 foliation within these phyllonites displays tops-down asymmetry and is associated with the L_2 down-dip lineation. These phyllonites are ductile normal faults and occur mainly in the western half of Domain I (Figure 46). The orientations of these ductile normal faults range from N20E to N30E.

Silicified Ridge

The silicified ridge creates a semi-linear topographic high that occurs through the center of the Tar River area and includes Mayfield Mountain and other knobs, such as Little Egypt Mountain to the north (Grimes, 2000) (Figure 47, Plate 1 and 2). Along this zone, the topographic highs contain silicified breccia boulders and the topographic low areas contain silicified breccia of metaigneous rock from the Carolina terrane. This silicified ridge is the Jonesboro fault (Figure 30) that extends to the north into the Kittrell and Henderson 1:24,000 quadrangles (Grimes, 2000; Blake, 2001). It extends to the southwest and forms the eastern boundary of the Deep River rift basin. The Jonesboro fault is a brittle normal fault and Domain I represents its hanging wall while Domain II represents its footwall. The Jonesboro fault strikes approximately N30E to N40E, and is associated with fractures and joints that overprint the surrounding ductile fabric elements. The Jonesboro fault truncates the Ruin Creek Gneiss and the Carolina terrane-Crabtree terrane boundary.

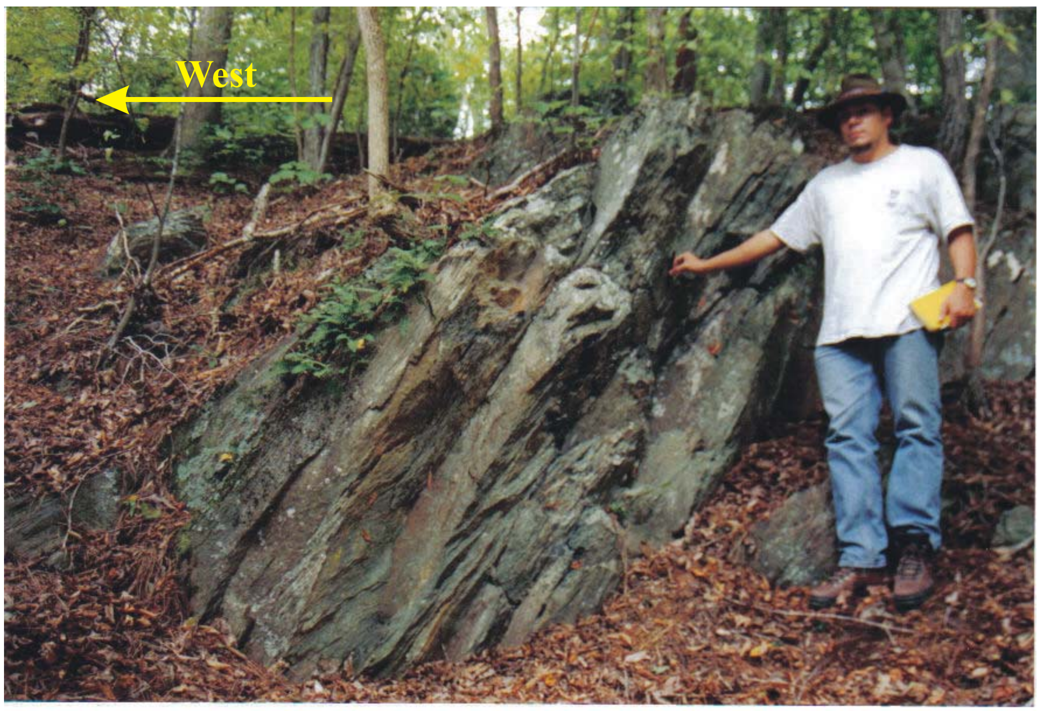


Figure 46: Outcrop photograph of the S_2 foliation in a shear zone within the Gibbs Creek pluton just west of CR 1622 bridge over the Tar River. Author for scale.

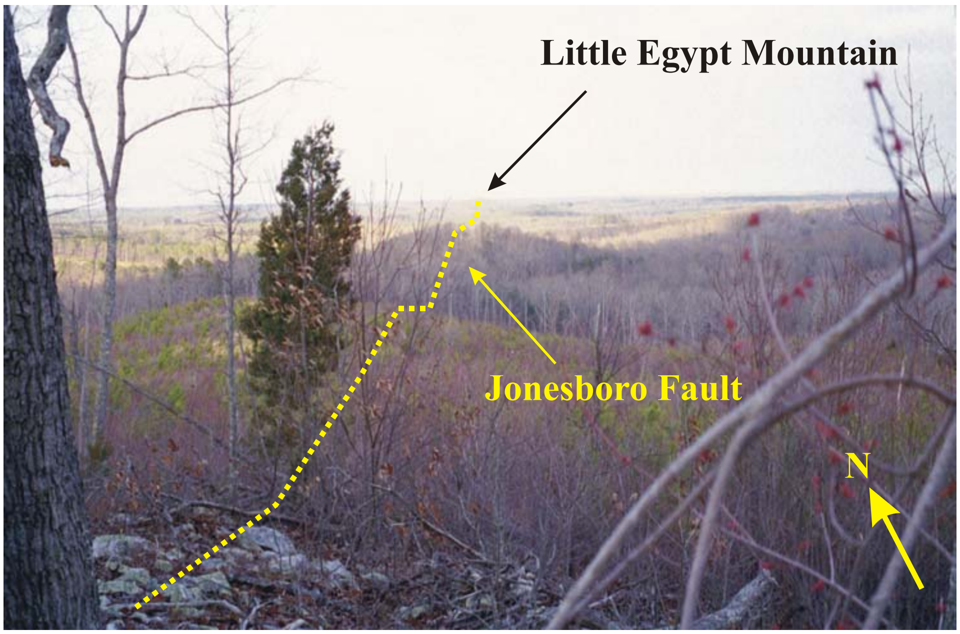


Figure 47: Outcrop photograph of the silicified breccia ridge of the Jonesboro fault and its trace from Mayfield Mountain northward across the Tar River area into the field area of Grimes (2000). Little Egypt Mountain is shown in the distance.

Domain II

The S_1 tectonite fabric overprinted the compositional layering S_0 and is penetrative within all terranes of Domain II (Figure 30). The Wilton pluton is predominately nonfoliated, but has a weak L_1 lineation along its eastern boundary (Figure 30). The S_1 tectonite fabric has a N10E to N20E orientation and is associated with a subhorizontal lineation L_1 that has a shallow plunge to the north and south. There are two linear traces where the S_1 tectonite fabric becomes more intense in the degree of dynamic recrystallization and contains a smaller grain size. L_1 is also more prevalent.

An east-west trending brittle fracture occurs within the Raleigh terrane (Figure 30). Other east-west trending brittle fractures occur along the western flank of the Wake-Warren anticlinorium (Heller, 1996; Stoddard, 1996; Stoddard and Heller, 1996; Heller and others, 1998; Grimes, 2000; Blake and others, 2003). These structures may have a common origin with other east-west oriented brittle faults and silicified ridges.

Falls Lake Fault

The boundary between the Middle Creek Gneiss of the Crabtree terrane and the Falls Lake Schist of the Falls Lake terrane is an area that experienced significant strain deformation (Figure 30). The contact between these two units is not well exposed and the true relationship is not completely known. However, the Middle Creek Amphibolite at station TR4 (Plate 2) contains multiple F_1 folds. The style ranges from asymmetrical and symmetrical, similar-style, multilayered folds that are reclined. There is a marked competence contrast between layers in this outcrop leading to some single layer fold development. Fine-grained quartz layers display characteristic ptygmatic-style folding

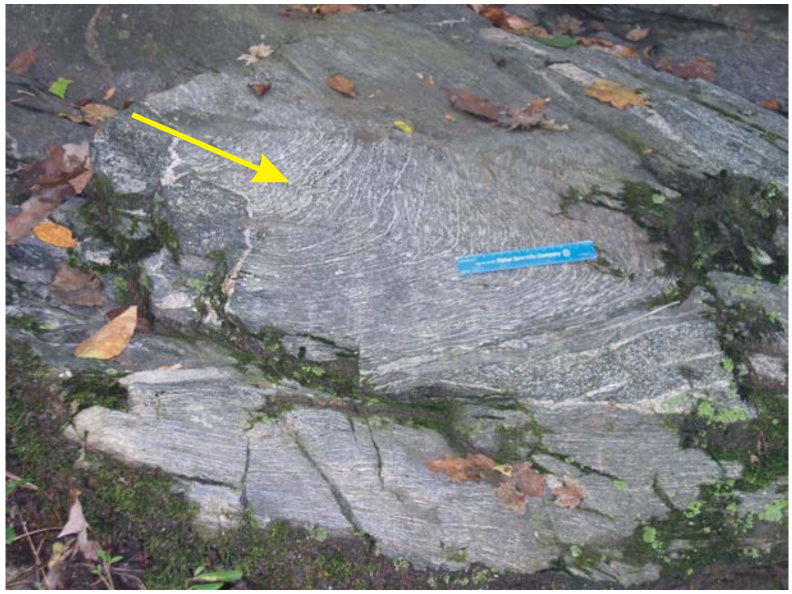
(Figure 48). Within the Falls Lake terrane, adjacent to the contact with the Crabtree terrane, F_1 folds are observed in the microscale (Figure 49).

Nutbush Creek Fault Zone

The Nutbush Creek fault encompasses a 1 km wide zone and is approximately centered on the Falls Leucogneiss. Strain associated with the fault extends west into the Middle Creek Gneiss and east into the Raleigh Gneiss (Figure 30) where recrystallization and significant grain size reduction occurs approximately a half kilometer on either side of the Falls Leucogneiss. The Falls Leucogneiss is an L>S-tectonite, or a pencil gneiss and typically weathers to thin pencil-shape fragments. Quartz and microcline define a rodding lineation, but a magnetite aggregate lineation is more distinctive. The Falls Leucogneiss is continuous within the Tar River area, but on a larger scale it pinches in and out along the western flank of the Wake-Warren anticlinorium.

A strong foliation, S_1 and a mineral stretching lineation, L_1 are observed within the zone. Kinematic indicators show dextral sense of shear and are associated with L_1, which contains a gentle plunge to the north or south. The layer parallel foliation within the units of the Nutbush Creek fault zone does not contain many distinct kinematic indicators, but occasionally biotite or white-mica "fish" display the tops-to-the-north or dextral shear sense. The dextral shear sense is compatible with observations of the Nutbush Creek fault zone along the length of its exposure on the western flank.

a.



b.

Figure 48: a) and b) Outcrop photographs of the Middle Creek Amphibolite in the Middle Creek Gneiss displaying multiple folding. b) A quartz-rich layer displays a ptygmatic-style fold. Scale bar is 15.24 cm long.

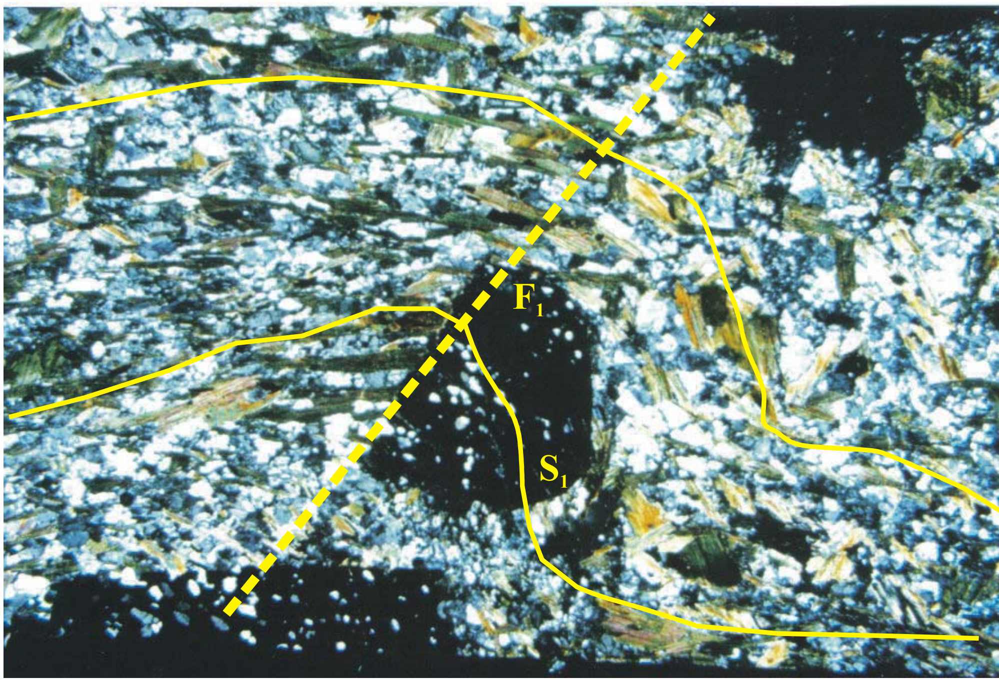


Figure 49: Photomicrograph of a garnet that contains quartz inclusions from the S_1 foliation. F_1 folded the S_1 foliation. Cross-polarized light. Magnification 1.25X. Field of view is 1.7 cm.

DISCUSSION

Introduction

The rocks of the eastern Piedmont of North Carolina experienced a complex origin and subsequent structural and metamorphic evolution. This study of the Tar River area is part of a USGS EDMAP project to refine mapping within the Henderson 1:100,000-scale topographic sheet, which is currently under investigation through the NCGS STATEMAP program.

This chapter will combine the lithodemic development of the Tar River area with its tectonothermal overprint to provide an upgraded geologic overview of the western flank of the Wake-Warren anticlinorium from the late Precambrian to the early Mesozoic. This history will be linked with information from other workers that have directly worked on or observed geology related to the Tar River area. In describing the lithodemes, the Jonesboro fault will be utilized as divider for separating Domains I and II as defined in the STRUCTURE CHAPTER. Domain I is located west of the Jonesboro fault, while Domain II is located to its east.

Lithodemes

Geologic mapping of the Tar River area identified a suite of lithodemic units within the Carolina, Falls Lake, Crabtree, and Raleigh terranes that are primarily the product of the accumulation of multiple igneous intrusions.

Domain I

Domain I is the Carolina terrane and the hanging wall graben to the Jonesboro normal fault. Its preservation of a variety of relict igneous features distinguishes it as a supercrustal terrane of the Carolina Zone.

Carolina Terrane

In the Carolina Terrane, the Gibbs Creek pluton is the dominate lithodeme and retains a relict phaneritic texture. The mineralogy and whole rock major element major element geochemistry indicate that the Gibbs Creek pluton is a tonalite and more minor granodiorite intrusion. Multi-element and REE geochemical diagrams demonstrate that the Gibbs Creek pluton has a calc-alkaline island-arc signature comparable with the origin of the Carolina Zone. The Gibbs Creek pluton has not been dated, but is probably late Proterozoic to Cambrian age, as compared with the timing of intrusion of the Vance Co. pluton located along strike to the north. The Vance Co. pluton is a metatrondhjemite having a zircon U-Pb date of 571 ± 17 Ma (LeHuray, 1983).

The Gibbs Creek pluton contains four types of enclaves that include Type 1 greenstone, Type 2 amphibolite, Type 3 metaultramafic, and Type 4 metagranitoid. The inclusion relationship of the enclaves with the Gibbs Creek pluton suggests that they may represent some of the oldest rocks in the Tar River area. REE geochemical data from a Type 2 amphibolite enclave indicate a MORB-like signature and this sample plots within the ocean-floor field on a Pearce and Cann (1973) (Ti/100)-Zr-(Y*3) tectonomagmatic discrimination diagram. This inclusion relationship and geochemical data may indicate that the Type 1, Type 2, and Type 3 enclaves represent oceanic substrate. The Type 4 enclaves share a similar mineralogy to the Gibbs Creek pluton and may represent an early pulse of magmatism of the pluton.

In contact with the Gibbs Creek pluton to the east is a foliated metagranodiorite. It shares similar relict features to the Gibbs Creek pluton, but is slightly more coarse-grained and K-feldspar enriched as well as being structurally overprinted. The contact between these two lithodemes is not well exposed in the Tar River area and is either intrusive or tectonic. This pluton is thought to be late Proterozoic to Cambrian in age and may share a similar calc-alkaline island-arc heritage with the Gibbs Creek pluton.

The Ruin Creek Gneiss lies to the east of the metagranodiorite. It is a mylonite having relict K-feldspar porphyroclasts that reflect its origin as an intrusive body. Its contact with the metagranodiorite is not well exposed and may either be intrusive or tectonic in nature. Due to its position in the Carolina terrane west of the Jonesboro fault, the Ruin Creek Gneiss was thought to be late Proterozoic to Cambrian in age. However, the strong ductile dextral transposition of this rock and lack of U-Pb age dates inhibits deciphering aspects of its history. In addition, Blake and Stoddard (2004) suggest that the trace element geochemical signature of the Ruin Creek Gneiss maybe similar to Alleghanian granitic intrusions lying to the east of the Tar River area. This hypothesis suggests that the Ruin Creek Gneiss has a late Paleozoic age and may be analogous to the 312 ± 15 Ma Rb-Sr whole rock (Kish and Fullagar, 1978) Buggs Island pluton along strike to the north.

A metagabbro dike intrudes the Gibbs Creek pluton and continues to the north out of the Tar River area (Carpenter, 1970; Blake and others, 2003; Pesicek, 2003). Its N-MORB-like trace element geochemical signature (Blake and Stoddard, 2004) and its crosscutting relationship with the Gibbs Creek pluton suggest that it represents a late-stage pulse of mafic magnetism in the development of the Carolina terrane.

Domain II

East of the Jonesboro fault, lithodemes within Domain II occur within the Falls Lake, Crabtree, and Raleigh terranes. These terranes lie on the footwall horst to the Jonesboro normal fault and are uplifted infrastructural terranes of the Carolina Zone.

Falls Lake Terrane

The Falls Lake terrane lies just east of the Jonesboro fault. It contains the Falls Lake Schist and metaultramafic rocks. Several protoliths for the Fall Lake terrane have been suggested.

To the south, Horton and others (1985, 1986) have interpreted the block-in-matrix appearance of the Falls Lake terrane as an accretionary prism mélange. Horton and others (1985, 1986) have interpreted the schist matrix of the Falls Lake terrane as reflecting a sedimentary protolith and the metamafic and metaultramafic blocks as being part of a dismembered ophiolite sequence (Moye, 1981; Stoddard and others, 1982). The metamafic and metaultramafic blocks range from mm to mappable-scale outcrops and include a variety of lithologies ranging from amphibolite, serpentinite, chlorite-actinolite schist, talc schist, and hornblendite. Blake and Stoddard (2004) suggest that the Falls Lake terrane is a deformed pluton with enclaves of metamafic and metaultramafic rocks incorporated into the intrusion. Goldberg (1994) dated an orthogneiss from the Falls Lake terrane south of the Tar River area and obtained a 590 Ma U-Pb zircon date. If this orthogneiss is a block within the matrix rocks of the mélange as suggested by Goldberg, then the 590 Ma date is the time of incorporation into the Falls Lake terrane. If it is a younger intrusion, then the 590 Ma date is the minimum age of the terrane (Horton and others, 1994). Alternatively, the 590 Ma date could be the date for the matrix as an intrusion and would be late Proterozoic to Cambrian in age.

Many of the metamafic and metaultramafic lithologies found in the Falls Lake terrane also are found within the Gibbs Creek pluton that lies across the Jonesboro fault to the west. Geochemical analysis of the Gibbs Creek pluton from the Carolina terrane and a matrix schist from Falls Lake terrane suggest that the samples display similar concentration trends on major element, N-MORB normalized multi-element, and chondrite-normalized REE diagrams. Both terranes display a block-in-matrix appearance. Similarities in geochemical trends also exist for amphibolite enclaves between the terranes. In contrast, these two terranes do differ in metamorphic grade.

The Crabtree Terrane

The Crabtree terrane hosts the Middle Creek Gneiss and contains felsic, intermediate, and mafic composition rocks along with metaultramafic rocks. A prominent amphibolite unit is the Middle Creek Amphibolite that lies adjacent to the Falls Lake fault. These rocks are interlayered and display sharp contacts and crosscutting relationships between the differing compositions. The gneisses are interpreted as having igneous intrusive protoliths. Major and trace element geochemical data from a biotite gneiss located within the Middle Creek Gneiss is similar to samples from the Carolina terrane and the Falls Lake terrane that display a calc-alkaline island-arc signature.

Further to the south on the western flank of the Wake-Warren anticlinorium, the Crabtree terrane contains gneissic and schistose rocks that are more felsic in composition. Two distinctive units in the Crabtree terrane to the south are a garnet-kyanite schist and a graphite schist (Parker, 1979; Wylie, 1984; Blake, 1986). These units led workers to assign a sedimentary protolith for some parts of the Crabtree terrane (Parker, 1979; Heller, 1996; Lumpkin and others, 1994). Other units show relict volcanic and plutonic textures. One of these intrusive units, the Crabtree Creek pluton has a 542 Ma U-Pb zircon date (Horton and Stern, 1994) and $^{207}Pb/^{206}Pb$ ages of 554, 564, and 566 Ma (Goldberg, 1994). This indicates that the Crabtree terrane is late Proterozoic to Cambrian in age.

The Raleigh Terrane

Within the Tar River area, the Raleigh terrane lies to the east of Crabtree terrane. The Raleigh terrane is composed of the Raleigh Gneiss, a interlayered felsic, intermediate, and mafic locally containing pods of metaultramafic rock. Crosscutting relationships of the Raleigh Gneiss in the Tar River area suggest igneous intrusive origins. Samples from the Raleigh Gneiss yield discordant 461 to 546 Ma $^{207}Pb/^{206}Pb$ zircon ages (Goldberg, 1994), which assigns a late Proterozoic to Cambrian age for the Raleigh terrane. However, more dates from samples across the terrane need to be obtained to have a more accurate age constraint on this complex multi-intrusive terrane.

The Raleigh terrane also contains the Falls Leucogneiss, an elongate felsic gneiss that to the south near Raleigh, is intrusive into the Raleigh Gneiss (Blake and others, 2001). Caslin and others (2001) reported a 545 to 543 ± 20 Ma, and Horton and Stern

(1994) reported a high precision 491 Ma $^{207}Pb/^{206}Pb$ zircon crystallization dates on the Falls Leucogneiss.

Two large granitic gneiss bodies intrude into the Raleigh terrane and are similar in composition to the Rolesville batholith, which intrudes the Raleigh terrane further to east outside the Tar River area. It appears that the two large granitic bodies and various pegmatites throughout Domain II are related to the Rolesville batholith, from which Schneider and Samson (2001) obtained a 280 Ma zircon U-Pb date for magnetism.

All terranes seem to correlate with the Carolina Zone as originally suggested by Hibbard and others (2002) and appear to represent different structural and metamorphic levels of equivalent rocks.

Tectonothermal Overview

Geologic mapping has allowed the determination of the tectonothermal activity that affects the terranes of the Tar River area. The overprinting metamorphism and structures of the Tar River area developed as a consequence of several regional events (Table 4). These events are synthesized into the regional tectonothermal context of Stoddard and others (1991) for the eastern Piedmont and the Wake-Warren anticlinorium.

Deformational event, D_e, is found within Type 2 amphibolite and Type 4 metagranitoid enclaves of the Gibbs Creek pluton. An M_e (greenschist to amphibolite facies) metamorphism accompanied D_e and together they produced the enclave S_e foliation. A greenschist facies is observed in all four types of enclaves, but it is difficult to determine whether it is a retrograde from M_e or an M_1 overprint on the enclaves. This makes it difficult to determine the exact grade of the M_e metamorphism. S_e, is a

Table 4: Tectonothermal history for the Tar River area. Information for D_2 was obtained from Stoddard and others (1991, 1994), and information on the related orogenies from Hibbard and others (2002).

Deformation Event	Metamorphic Event	Fabric Elements Produced	Structures Produced	Related Tectonic Orogeny
D_4	Late-M_2?	Not Observed	Brittle Normal Jonesboro Fault, Fractures, and Silicified Zones	Late Triassic Rifting
D_3 to D_4 Transition?	Late-M_2?	S_2, L_2	Ductile Normal and Ductile-Brittle Faults within the Carolina Terrane	Early Rift Stage
D_3	M_2	S_1, L_1, F_1	Dextral Ductile Faults within the Carolina Terrane, Falls Lake Fault, and Nutbush Creek Fault	Alleghanian
D_2	Not Observed	Not Observed	Falls Lake Fault? (Stoddard and others, 1994)	Acadian?
D_1	M_1	Not Observed	Not Observed	Taconic
D_e	M_e	S_e	Not Observed	Pre-Taconic ca. 617 to 544 Ma?

penetrative foliation that is planar in the Type 2 amphibolite and convoluted in the Type 4 metagranitoid enclaves.

D_1 deformation was not observed in the Tar River area, although it is regionally considered to be associated with the greenschist facies (chlorite zone) M_1 metamorphism and the Taconic orogeny (Kish and others, 1979; Harris and Glover, 1988; Noel and others, 1988; Offield and others, 1995). M_1 overprints the rocks within Domain I and is the characteristic metamorphism of what Hibbard and others (2002) describe as observed in the superstructural terranes. M_1 is thought to be Late Ordovician in age, and part of the Taconic orogeny based on 455 and 456 Ma $^{40}Ar/^{39}Ar$ whole rock dates from samples within the main portion of the Carolina terrane in the central Piedmont (Kish and others, 1979; Harris and Glover, 1988; Noel and others, 1988; Offield and others, 1995). The M_1 metamorphism and the plutonic nature of the rocks with the Carolina terrane of the Tar River area are analogous to rocks just to the north, which are relatively undeformed metaigneous rocks having relict phaneritic textures (Carpenter, 1970; Hadley, 1973; Wooten and others, 2002; Blake and others, 2003; Pesicek, 2003). The Tar River area rocks within the easternmost Carolina terrane continue around the Durham basin and directly link with the rocks of the Virgilina and Albemarle sequences of the Carolina terrane to the west (Hibbard and others, 2002; Wooten and others, 2002).

D_2 was also not observed in the Tar River area, but according to Stoddard and others (1991, 1994), it is associated with middle to late Paleozoic regional thrust faults, such as the Falls Lake fault zone. The contact that is the Falls Lake fault zone within the Tar River area is not well exposed and the kinematic development of the fault is not known. However, deformation on either side of this fault zone displays dextral movement.

D_3 is an Alleghanian event, along with regional M_2 metamorphism, has produced the S_1 foliation and L_1 lineation in Domain II and locally in Domain I. M_2 is a chlorite zone greenschist facies to kyanite and sillimanite zone amphibolite facies metamorphism that increases in grade eastward across the western flank with the highest grade exposed in hinge of the Wake-Warren anticlinorium. M_2 is associated with the infrastructural rocks within the Carolina Zone of Hibbard and others (2002). Faults associated with D_3 are the Nutbush Creek, Falls Lake, and local mylonite and phyllonite zones within the Gibbs Creek pluton.

Although relatively undeformed, the Gibbs Creek pluton contains narrow dextral high strain zones indicative of the D_3 deformation Alleghanian orogeny. These high strain zones contain mylonite and phyllonite and the S_1 foliation and subhorizontal L_1 lineation. Many strike N20E to N30E and are steeply dipping. The D_3 high strain zones in the Carolina terrane contain M_2 greenschist facies metamorphism and have been documented to the north and south of the Tar River area (Wooten and others, 2002; Blake and others, 2003; Pesicek, 2003). The metagranodiorite and Ruin Creek Gneiss define a D_3 high strain zone along the eastern boundary of the Carolina terrane. The Ruin Creek Gneiss also truncates a portion of the Wilton pluton.

As mentioned above the contact between the Falls Lake terrane and the Crabtree terrane is the Falls Lake fault zone and is not well exposed in the Tar River area. Although thought to be a D_2 thrust fault (Stoddard and others, 1991, 1994), no evidence to support this was found. However, along either side of this fault the S_1 foliation was observed. This study considers the Falls Lake fault zone to be related to D_3 fault or has been overprinted with D_3 deformation.

The Nutbush Creek fault zone within the Tar River area has a distinctive S_1 N15E strike with a subhorizontal stretching lineation, L_1. The Falls Leucogneiss lies within the Nutbush Creek fault zone along with portions of the Crabtree and Raleigh terranes.

D_4 deformation is related to the Triassic breakup of Pangea. D_4 produced the S_2 foliation and the down-dip L_2 lineation with tops-down kinematic indicators found within the phyllonite zones in the Gibbs Creek pluton. These are ductile normal high strain zones that increase in concentration westward towards the Fishing Creek fault west of the Tar River area. These ductile normal faults also created slick surfaces found within a portion of the metagranodiorite. D_4 also caused the brittle normal faulting of the Jonesboro fault creating a zone of silicified breccia and silicified brecciated country rock and a half-graben to the west and an uplifted horst on the east.

Geologic History

Horton and others (1989) first subdivided rock types into terranes across the Wake-Warren anticlinorium. This subdivision was based upon composition of rock, metamorphism, and bounding faults. However, this study observed that similarities exist in rock appearance and composition across terrane boundaries. Jackson (1997) defines a terrane as a fault-bounded body of rock of regional extent, characterized by a geologic history different from that of contiguous terranes or bounding continents. A terrane is generally considered to be a discrete allochthonous fragment of oceanic or continental material added to a craton at an active margin by accretion.

The infrastructural and superstructural terranes of the Tar River area and western flank of the Wake-Warren anticlinorium all appear to share similarities related to a mutual island-arc development in the Carolina Zone (Hibbard and others, 2002; Blake and Stoddard, 2004). Through mapping and geochemical and tectonothermal analyses, it appears that some rocks within terranes display similar attributes and may not be exotic to one another as the terrane definition states. In discussing the geologic history, it is also important to describe Carolina Zone and its stages of magmatic development (Hibbard and others, 2002) in order to better understand the geologic significance of the Tar River area.

Hibbard and Samson (1995) grouped the terranes and sequences of the eastern Piedmont of Virginia, North and South Carolina, Georgia, and Alabama that appear to have a common island-arc origin and called it the Carolina Zone. The terranes containing low grade metamorphic rocks are suprastructural and include the Carolina (Albemarle, South Carolina, Cary, and Virgilina sequences), Spring Hope, Roanoke Rapids, Augusta, and Milledgeville terranes (Hibbard and others, 2002). The terranes containing higher grade metamorphic rocks are infrastructural and include the Charlotte, Falls Lake, Crabtree, Raleigh, Triplet, Dreher Shoals, Savannah River, and Uchee terranes (Hibbard and others, 2002).

Hibbard and others (2002) then separate the peri-Gondwanan magmatic and depositional history of the Carolina Zone into three stages. Stage I defines pre-600 Ma island-arc magmatic activity within the zone. Evidence for this stage is observed within the Virgilina sequence of the Carolina terrane and the Spring Hope and Roanoke Rapids terranes. In the Virgilina sequence has U-Pb zircon dates that range from 633 to 612 Ma

(Wortman and others, 2000), and contains juvenile felsic igneous rocks were thought to have generated on an oceanic substrate (Hibbard and others, 2002). However, the igneous, volcanic, and sedimentary rocks of the Spring Hope and Roanoke Rapids terranes suggest formation from a more evolved oceanic crust perhaps containing some continental crust influence (Hibbard and others, 2002).

Based upon this study, enclaves within the Gibbs Creek pluton are thought to have been formed Stage I. The enclaves of the Gibbs Creek pluton and the Falls Lake terrane contain MORB-like REE signatures and are possibly oceanic substrate. The Type 1 greenstone and Type 2 amphibolite are possibly metabasalts whereas the Type 3 metaultramafic rocks are possibly metaperidotites. The origin of the D_e deformation is unclear, however an early deformation that folded and faulted volcanic rocks was observed in the Virgilina sequence of the Carolina terrane (Glover and Sinha, 1973; Harris and Glover, 1988). Hibbard and Samson (1995) noted in the Virgilina sequence that a post-tectonic pluton having a 546 ± 2 Ma U-Pb zircon date intrudes foliated metavolcanic rock having a 612 +5/-2 U-Pb zircon date (Wortman and others, 2000). This D_e deformation within the enclaves of the Gibbs Creek pluton could perhaps correlate with the pre-600 Ma deformation from the Virgilina sequence and predates Stage 2 development of the Carolina Zone.

Stage II represents the main pulse magmatism and deposition during intra-arc rifting from 590-569 Ma. This stage is observed in the felsic and mafic rocks that occur within the pyroclastic and plutonic Cary sequence and the Charlotte, Crabtree, and Spring Hope terranes. Lying between the Charlotte terrane and Inner Piedmont are mafic rocks that intruded felsic rocks and are comparable to western Pacific rifted arc terranes

(Dennis and Shervais, 1991; Dennis and Shervais, 1996; Shervais and others, 1996). Hibbard and others (2002) suggest this arc rifted was followed by sedimentation as observed with the metasedimentary units of the Crabtree terrane (Parker, 1979; Wylie, 1984; Blake, 1986) and perhaps in the Spring Hope and the Carolina terranes.

In the Tar River area, the Gibbs Creek pluton, Falls Lake Schist, Middle Creek Gneiss, Middle Amphibolite, Raleigh Gneiss, and the Falls Leucogneiss are thought to have originated as igneous intrusions during Stage II. These lithodemes contain either relict textures or features that suggest an intrusive protolith. Although, the Falls Lake Schist was interpreted has being an accretionary prism mélange (Horton and others, 1986), its relict features and geochemical signature possibly suggest an intrusive origin. These units along the western flank of the Wake-Warren anticlinorium share a common late Proterozoic to Cambrian age and an island arc calc-alkaline geochemical signature.

Stage III occurred between 550 Ma and the early Cambrian and produced magmatic, rifting, and depositional environments. This stage is observed in a variety of the Carolina Zone terranes. Some of the more notable areas are the mafic and ultramafic volcanic rocks of the Cary sequence and the Charlotte terrane. Sedimentary rocks are observed within the Albemarle and South Carolina sequences and the Spring Hope and Augusta terranes. Within this stage, some rocks from these terranes with the exception of the Augusta, display Nd signatures that indicate the involvement of a continental crust (Mueller and others, 1996; Hibbard and others, 2002).

The metagabbro dike within the Tar River area is perhaps representative of this continued rifting, magmatic, and depositional Stage III. The metagabbro contains a MORB-like REE geochemical signature and intruded the Gibbs Creek pluton. This relationship with the Gibbs Creek pluton possibly represents mafic magmatism during rifting of the Carolina Zone.

Farrar (1984; 1985a, b) alternatively believes that the terranes are the southern extension of the Grenville Goochland terrane in Virginia. This hypothesis is based on M_g granulite facies assemblages observed within the Goochland terrane of Virginia, and sillimanite, orthopyroxene, and clinopyroxene assemblages observed within rocks of the Raleigh terrane in the northernmost portion of the Wake-Warren anticlinorium. However, the Raleigh terrane in the Tar River area or further to the south along the western flank does not contain those minerals. Farrar (1985b) also described the Falls Leucogneiss as a peralkaline A-type granite related to late Proterozoic rifting of Laurentia. Farrar and Owens (2001) believe that the Falls Leucogneiss intruded thinned crust of Laurentia around 600 Ma. However, the Falls Leucogneiss appears to have intruded Carolina Zone rocks and not Goochland equivalents based on mineralogy, metamorphic grade, and the age relationships of the Raleigh Gneiss which are more similar to the Falls Leucogneiss. These late Proterozoic ages for the Raleigh Gneiss more similar to the Carolina terrane and Carolina Zone dates, which are much younger than the 1.1 Ga age of the rocks from the Goochland terrane. Finally, the Lake Gordon and Hylas faults separate the Goochland terrane from the rocks of the Wake-Warren anticlinorium (Sacks, 1999). The terranes of the western flank do not appear to correlate mineralogically, geochronologically, or geochemically with the Goochland terrane and do not appear to be its southern extension.

Inconsistency exists for the substrate that the Carolina Zone was built upon. Based on a geographical trend with other peri-Gondwanan terranes (Secor and others, 1983; Nance and Murphy, 1996), Acado-Baltic fossil evidence (Samson and others, 1990), and a deformation that predates the Appalachian orogenic cycle (Hibbard and Samson, 1995; Dennis and Wright, 1997a; Barker and others, 1998), the Carolina Zone is thought to have formed adjacent to Gondwana and is exotic to Laurentia (Hibbard and others, 2002).

Nd isotope signatures and inherited and detrital zircon ages for many of the terranes suggest a variety of substrates that the Carolina Zone was built upon and it is likely that the Carolina Zone is not part of the Avalon terrane (Samson, 1995). Some areas of the Carolina Zone reflect a juvenile crust and others reflect a more involved crust.

Wortman and others (2000) suggest that the juvenile Nd isotopic character of the Virgilina sequence is an indication that this sequence formed on oceanic crust away from continental crustal influence. Mueller and others (1996) thought U-Pb isotopic data for zircons of Carolina terrane rocks strongly suggest that the basement to the Carolina Zone was Mesoproterozoic and the crust was involved in the Grenville orogeny. Mueller and others (1996) also state that a peri-Laurentian arc developed on Grenville basement is a possibility.

Nance and Murphy (1996) noted differences in isotopic signatures between the Avalonian-Cadomian terranes and the Carolina Zone and Suwannee terrane, and suggest that the Carolina Zone and Suwannee terrane display a more evolved crustal component, possibly Grenville in age. Nance and Murphy (1996) suggest that the Carolina Zone and Suwannee terrane may have derived from peri-Amazonian positions.

Ingle and others (2003) observed similarities between the rocks of the Carolina Zone and rocks from the northern margin of South America. Ingle and others (2003) state that the Orinoquian-Sunsas, the Trans-Amazonian, and the Central Amazonian orogenic zones are candidates for basement correlatives to the Carolina Zone. Other workers such as Keppie and others (2003) are using modern analogues as models for the birth and development of the Carolina Zone and other peri-Gondwanan terranes.

The Carolina Zone experienced this collision and transform movement with Laurentia from the Taconic through the Alleghanian orgenies. During the Taconic orogeny, collision with Laurentia produced the regional M_1 greenschist facies metamorphism and D_1 deformation. M_1 is observed within the superstructural Carolina Zone terranes, which is the Carolina terrane in Domain I of the Tar River area.

Subsequent D_2 deformation (Acadian to early Alleghanian?) produced major thrust faults within the eastern Piedmont. The Falls Lake fault on the western flank of the Wake-Warren anticlinorium is interpreted as a D_2 thrust based on the D_3 Raleigh antiform, which folds the fault (Stoddard and others, 1994). Though Stoddard and others (1991, 1994) interpret the Falls Lake fault as a D_2 thrust, some contacts are in question and the fault may contain areas that are overprinted or reactivated with D_3 elements (Blake and others, 2001). In the Tar River area, though poorly exposed, the Falls Lake fault displays a D_3 dextral movement on both sides and is interpreted as an Alleghanian fault zone.

The Alleghanian orogeny produced a regional amphibolite facies metamorphism, M_2, and the D_3 deformation, and together they produced S_1 and L_1. This is observed within high strain zones within Domain I and within the Falls Lake, Crabtree, and

Raleigh terranes in Domain II. The high strain zones within Domain I overprint the metagranodiorite and the Ruin Creek Gneiss. Also, the D_3 deformation produced major fault zones within Domain II, plutons (Rolesville batholith and Wilton pluton), and folds (Raleigh antiform and Wake-Warren anticlinorium). The Nutbush Creek fault zone (Casadevall, 1977) is a major D_3 Alleghanian shear zone of the Eastern Piedmont fault system (Hatcher and others, 1977) that has been traced 200 km from north-central North Carolina into southern Virginia and is generally one to three km wide (Druhan and others 1994).

Similar faults are observed along strike to the north and south of the Nutbush Creek fault zone. In Virginia, Maryland, and into Pennsylvania, the Hylas fault zone (Bobyarchick and Glover, 1979), Pleasant Grove shear zone (Krol and others, 1999), and Huntingdon Valley shear zone (Valentino, 1999) display similar dextral kinematic indicators and timing with the Nutbush Creek fault zone. To the south, the Irmo shear zone (Secor and others, 1986b) in South Carolina may be the southern extension of the Nutbush Creek fault zone. Timing for major faulting within the Nutbush Creek is bracketed between 312 to 285 Ma. This is based on a 312 ± 15 Ma Rb-Sr whole rock date for the deformed Buggs Island pluton (Kish and Fullagar, 1978) and 285 ± 10 Ma Rb-Sr whole rock date for the relatively undeformed Wilton pluton (Fullagar and Butler, 1979). The Wilton pluton does display an L_1 fabric along its boundaries and may indicate younger continued movement through 285 Ma.

In the Tar River area, the Nutbush Creek fault zone is centered on the Falls Leucogneiss. However, strain from the fault extents about 100 m into the Crabtree terrane to the west and 100 m into the Raleigh terrane to the east. The S_1 foliation and L_1

lineation in this zone display dynamic recrystallization. Within the Falls Leucogneiss, L_1 is more pervasive creating an L-tectonite.

Following the Alleghanian orogeny, Pangea started to rift and created crustal thinning during the Mesozoic formation of the Durham basin on the western flank. Some possible early indications of this rifting are observed within the Tar River area as ductile-brittle and ductile normal behavior. Ductile-brittle behavior occurs as cataclastic material between and parallel with the D_3 foliation in the Ruin Creek Gneiss and kink folds and microfaulting within plagioclase crystals within the metagranodiorite. To the north in the Virginia Piedmont along the Hylas fault zone, similar signs of ductile-brittle transition were recorded and are thought to have occurred around 260 Ma (Bobyarchick and Glover, 1979; Gates and Glover, 1989).

Other D_4 faults are also mapped along the western flank of the Wake-Warren anticlinorium and occur just east of the Durham basin. These D_4 faults are ductile normal and are found within the Gibbs Creek pluton. On the southwestern flank of the Wake-Warren anticlinorium within the Buckhorn Dam complex of the Carolina terrane, there is mylonite ranging from protomylonite to ultramylonite that range from 2 cm to several meters in thickness and show tops-down-to-the-west or normal displacement (Blake and others, 2001). Ductile normal faulting the Coles Branch Phyllite adjacent to the Jonesboro fault on the southwestern flank of the Wake-Warren anticlinorium yielded a 255 ± 2 Ma $^{40}Ar/^{39}Ar$ date (Hames and others, 2001). Also, ductile normal faulting is found within Umstead State Park, just west of Raleigh (Blake and others 2001), and to the north of the Tar River area west of the Jonesboro fault (Wooten and others, 2002;

Blake and others, 2002; Pesicek, 2003). These D_4 ductile-brittle and ductile normal faults may indicate an initial late Permian rifting of Pangea before the brittle breakup.

The D_4 deformation caused the formation of half graben structures along the western flank of the Wake-Warren anticlinorium. The most obvious of these structures are the sub-basins of the Deep River basin, the Wadesboro, Sanford, and Durham. The faults that created these basins are the Jonesboro and the Fishing Creek brittle normal faults that form the eastern boundary of the basins (Carpenter, 1970; Parker, 1979; Heller, 1996; Grimes, 2000; Blake and others, 2002).

The most distinguishing feature in the Tar River area related to the D_4 deformation are east-west trending brittle faults (Heller, 1996; Grimes, 2000) and the brittle normal Jonesboro fault, which is a continuation of the normal fault that forms the eastern boundary of the Durham basin to the south. The Jonesboro fault creates a metamorphic discontinuity within the Tar River area, which juxtaposes greenschist facies against amphibolite facies. Within the Tar River area the Jonesboro fault contains brecciated rock (typically rock form the Carolina terrane) and silicified breccia that form topographic peaks. The Jonesboro fault overprints the adjacent D_3 Ruin Creek Gneiss, which lies to the west in the Carolina terrane. Mesoscale and microscale fractures crosscut the D_3 foliation and occur to the west and to the east of the fault. The Jonesboro fault also truncates the 285 Ma Wilton pluton. Timing of D_4 brittle normal deformation and breakup of Pangea is thought to the Mesozoic, specifically Triassic (Fullagar and Butler, 1979), however the 255 Ma date of Hames and others (2001) may indicate a progressive breakup originating in the late Permian.

CONCLUSIONS

1. The Tar River area contains an assemblage of late Proterozoic to Cambrian metaigneous rocks that originated in a peri-Gondwanan calc-alkaline island-arc known as the Carolina Zone. Geologic mapping was used to separate the rocks into four lithotectonic terranes that include the Carolina, Falls Lake, Crabtree, and Raleigh terranes.

   The Carolina terrane contains the metamorphosed Gibbs Creek pluton, a late Proterozoic intrusion of tonalite and subordinate granodiorite. This pluton contains four types of enclaves that include: 1) Type 1 greenstone, 2)Type 2 amphibolite, 3) Type 3 metaultramafic rocks, and 4) Type 4 metagranitoid. A late Proterozoic metagranodiorite is exposed along the eastern contact of Gibbs Creek pluton. In addition, a map-scale metagabbro dike that is possibly late Proterozoic in age crosscuts the Gibbs Creek pluton. The Ruin Creek Gneiss defines the eastern limits of the Carolina terrane and is a mylonitic granite gneiss that may represent a late Paleozoic granitic intrusion.

   The Falls Lake terrane contains the Falls Lake Schist, a possible metaigneous lithodeme that is late Proterozoic in age. Blocks of metaultramafic talc chlorite actinolite schist also occur within the Falls Lake terrane.

   The Crabtree terrane contains interlayered felsic, intermediate, and mafic gneiss known as the Middle Creek Gneiss and Middle Creek Amphibolite that are thought to be late Proterozoic in age. Blocks of metaultramafic talc chlorite actinolite schist also occur within the Crabtree terrane.

The Raleigh terrane contains interlayered felsic, intermediate, and mafic gneiss that define the late Proterozoic Raleigh Gneiss and the Cambrian Falls Leucogneiss. The Raleigh Gneiss also includes minor bodies of metaultramafic talc chlorite actinolite schist.

The late Paleozoic Wilton pluton, two smaller granitic bodies, and small-scale pegmatite dikes and sills crosscut the Falls Lake, Crabtree, and Raleigh terranes. These intrusions are related to the late Paleozoic Rolesville batholith.

2. These metaigneous and plutonic rocks are subdivided into two structural domains that experienced a complex tectonothermal history that spans the late Proterozoic into the early Mesozoic. Domain I includes the Carolina terrane and lies west of the Jonesboro normal fault. Domain II lies east of this fault and includes the Falls Lake, Crabtree, and Raleigh terranes.
3. A pre-Taconic greenschist to amphibolite facies metamorphism, M_e, is contained within enclaves of the Gibbs Creek pluton in Domain I. A regional greenschist facies metamorphism, M_1, possibly Taconic in age, is preserved within Domain I. An M_2 Alleghanian amphibolite facies metamorphism is preserved within Domain II.
4. D_e is a possible pre-Taconic deformation that may correlate with an early deformation observed in the Virgilina sequence of the Carolina terrane (Hibbard and others, 2002). D_e in the Type 2 amphibolite enclaves is a planar foliation S_e, whereas in the Type 4 metagranitoid enclaves, S_e is irregular and folded on the mesoscale. The D_1 and D_2 deformations of Stoddard and others (1991) that are

related to collision of the Carolina Zone with Laurentia were not observed within the Tar River area, although M_1 may record this tectonothermal event.

A D_3 Alleghanian deformation produced a northeast-striking S_1 mylonite foliation, subhorizontal L_1 stretch lineation, and minor F_1 folds during the transpressional collision between Laurentia and Gondwana and formation of Pangea. S_1 and L_1 are associated with penetrative ductile dextral displacement in high strain zones that overprint the Ruin Creek Gneiss and the metagranodiorite within Domain I. D_3 also occurs penetratively throughout Domain II with high strain concentrations forming the terrane bounding Falls Lake and Nutbush Creek fault zones between the Falls Lake and Crabtree terranes and the Crabtree and Raleigh terranes, respectively.

The western portions of Domain I also preserve several D_4 ductile-brittle normal faults that contain a northeast-striking S_2 phyllonite foliation and L_2 dip-parallel stretch lineation. D_4 deformation also produced a major terrane-bounding brittle normal fault, the Jonesboro fault, marked by a silicified breccia ridge and silicified country rock breccia. The silicified ridge separates the Domain I graben from Domain II horst and highlights the distinct metamorphic discontinuity between rocks on either side of the Jonesboro fault. The formation of this normal fault, combined with the intrusion of Jurassic-age diabase dikes that crosscut all terranes within the Tar River area, are attributed to the initial breakup and rifting of the Pangean supercontinent.

5. The Gibbs Creek pluton is compositionally a tonalite and subordinate granodiorite body that has metamorphosed mafic, intermediate, and ultramafic enclaves.

Intermediate schist and gneiss of the Falls Lake and Crabtree terranes contain metamorphosed mafic and ultramafic enclaves. These three terranes contain similar major and trace element abundances and show similar trends on QAP, TAS, Harker, multi-element, and REE diagrams. It may be possible that these three terranes contain the same rock type, but are separated by the Jonesboro fault and are at different grades of metamorphism.

6. Late Proterozoic to Cambrian rocks along the western flank of the Wake-Warren anticlinorium terranes display similar lithologic, geochemical, and geochronological relationships that are compatible with the Stage II magmatic development of the Carolina Zone. These fault-bounded rocks share a common peri-Gondwanan calc-alkaline island-arc origin and do not appear to be exotic to one another, but are exotic to Laurentia. Consequently, the separation of metaigneous rocks into distinct lithotectonic terranes along the western flank of the Wake-Warren anticlinorium may need to be reevaluated.

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APPENDIX

Appendix A. Orientation data from station locations within the Tar River area. F.E. = fabric element.

	Foliation		F.E.	Lineation		F.E.
Station Number	Strike	Dip		Trend	Plunge	
TR01-3						
TR01-4						
TR01-5	N40E	61NW	S_1			
TR01-6						
TR01-7	N40E	85NW	S_1			
TR01-8						
TR01-9						
TR01-10						
TR01-11	N28E	72NW	S_1			
TR01-12	N42E	85SE	S_1			
TR01-13	N15E	90	S_1			
TR01-14	N36E	90	S_1			
TR01-15	N24E	85SE	S_1			
TR01-16	N34E	78NW	S_1	N32E	2	L_1
TR01-17	N60E	89NW	S_1			
TR01-18	N34E	81NW	S_1			
TR01-19	N18E	83NW	S_1	N17E	11	L_1
TR01-20	N30E	78NW	S_1			
TR01-21	N33E	79NW	S_1			
TR01-22	N23E	80NW	S_1			
TR01-23	N20E	85NW	S_1			
TR01-24	N15E	90	S_1			
TR01-25	N14E	78NW	S_1			
TR01-26	N20E	80NW	S_1			
TR01-27	N15E	81NW	S_1			
TR01-28	N46E	80NW	S_1	N42E	14	L_1
TR01-29						
TR01-30						
TR01-31						
TR01-32						
TR01-33						
TR01-34	N20E	50NW	S_1			
TR01-35				S10E	26	L_1
TR01-36				S20E	16	L_1
TR01-37	N20E	72NW	S_1			
TR01-38						
TR01-39	N25E	80NW	S_1			
TR01-40	N25E	85NW	S_1			
TR01-41	N30E	69NW	S_1			
TR01-42	N22E	80NW	S_1			
TR01-43	N20E	80NW	S_1			
TR01-44	N25E	85NW	S_1			
TR01-45	N20E	85SE	S_1			
TR01-46						
TR01-47	N20E	90	S_1			
TR01-48	N25E	85SE	S_1			
TR01-49	N25E	80NW	S_1			
TR01-50						
TR01-51						
TR01-52						
TR01-53						
TR01-54						

	Foliation		F.E.	Lineation		F.E.
Station Number	Strike	Dip		Trend	Plunge	
TR01-65	N30E	80NW	S_1			
TR01-66						
TR01-67	N30E	80NW	S_1			
TR01-68						
TR01-69	N28E	80NW	S_1			
TR01-70						
TR01-71						
TR01-72						
TR01-73	N45E	90	S_1			
TR01-74						
TR01-75	N33E	90	S_1			
TR01-76	N45E	90	S_1			
TR01-77	N30E	90	S_1			
TR01-78						
TR01-79						
TR01-80						
TR01-81						
TR01-82						
TR01-83						
TR01-84						
TR01-85						
TR01-86						
TR01-87						
TR01-88						
TR01-89						
TR01-90						
TR01-91						
TR01-92						
TR01-93						
TR01-94						
TR01-95						
TR01-96						
TR01-97						
TR01-98						
TR01-99						
TR01-100						
TR01-101						
TR01-102						
TR01-103						
TR01-104						
TR01-105						
TR01-106						
TR01-107	N30E	70NW	S_1	N25E	15	L_1
TR01-108	N35E	70NW	S_1			
TR01-109				N30E	0	L_1
TR01-110				N30E	0	L_1
TR01-111	N30E	80SE	S_1			
TR01-112				N30E	0	L_1
TR01-113						
TR01-114				N30E	0	L_1
TR01-115	N35E	90	S_1			
TR01-116	N30E	90	S_1			

TR01-55						
TR01-56	N10E	90	S_1			
TR01-57						
TR01-58	N15E	65NW	S_1			
TR01-59				N15E	20	L_1
TR01-60	N12E	90	S_1			
TR01-61						
TR01-62				N10E	0	L_1
TR01-63				N15E	20	L_1
TR01-64	N30E	70NW	S_1			
TR01-127						
TR01-128						
TR01-129						
TR01-130						
TR01-131						
TR01-132						
TR01-133						
TR01-134						
TR01-135						
TR01-136						
TR01-137						
TR01-138						
TR01-139						
TR01-140						
TR01-141						
TR01-142						
TR01-143						
TR01-144						
TR01-145						
TR01-146	N45E	45NW	S_1			
TR01-147						
TR01-148	N25E	45SW	S_1	S25W	45	L_1
TR01-149						
TR01-150						
TR01-151						
TR01-152						
TR01-153						
TR01-154						
TR01-155						
TR01-156						
TR01-157						
TR01-158						
TR01-159						
TR01-160						
TR01-161						
TR01-162						
TR01-163						
TR01-164						
TR01-165						
TR01-166						
TR01-167						
TR01-168						
TR01-169						
TR01-170				N20E	18	L_1
TR01-171				N20E	20	L_1
TR01-172				N35E	15	L_1
TR01-173				N25E	15	L_1
TR01-174				N20E	20	L_1
TR01-175						
TR01-176				N25E	23	L_1
TR01-177						

TR01-117	N30E	90	S_1			
TR01-118						
TR01-119						
TR01-120	N10E	90	S_1			
TR01-121						
TR01-122						
TR01-123						
TR01-124						
TR01-125	N45E	50SE	S_1			
TR01-126	N48E	85SE	S_1			
TR01-191				N18E	20	L_1
TR01-192	N26E	90	S_1			
TR01-193	N10E	90	S_1			
TR01-194						
TR01-195	N-S	70W	S_1			
TR01-196				S60W	10	L_1
TR01-197	N15E	80NW	S_1			
TR01-198	N25E	90	S_1			
TR01-199						
TR01-200				N12E	10	L_1
TR01-201						
TR01-202						
TR01-203						
TR01-204				N18E	0	L_1
TR01-205	N20E	85SE	S_1	N20E	0	L_1
TR01-206	N18E	80NW	S_1			
TR01-207						
TR01-208	N9E	85SE	S_1			
TR01-209	N10E	82NW	S_1			
TR01-210	N18E	85SE	S_1	N18E	10	L_1
TR01-211	N15E	83NW	S_1			
TR01-212	N17E	90	S_1			
TR01-213	N18E	80NW	S_1	N18E	8	L_1
TR01-214	N10E	84NW	S_1			
TR01-215	N12E	85SE	S_1			
TR01-216						
TR01-217						
TR01-218						
TR01-219	N10E	81NW	S_1			
TR01-220	N10E	78NW	S_1	N8E	8	L_1
TR01-221	N8E	80NW	S_1	N8E	10	L_1
TR01-222						
TR01-223						
TR01-224						
TR01-225						
TR01-226						
TR01-227						
TR01-228						
TR01-229						
TR01-230						
TR01-231	N8E	78NW	S_1	N8E	0	L_1
TR01-232						
TR01-233						
TR01-234						
TR01-235						
TR01-236						
TR01-237						
TR01-238						
TR01-239						
TR01-240						
TR01-241						

TR01-178	N28E	90	S_1			
TR01-179	N28E	85NW	S_1			
TR01-180	N25E	80NW	S_1			
TR01-181	N30E	90	S_1			
TR01-182				N35E	10	L_1
TR01-183	N50E	85SE	S_1			
TR01-184	N33E	85NW	S_1			
TR01-185	N25E	90	S_1			
TR01-186	N28E	85SE	S_1			
TR01-187				N33E	23	L_1
TR01-188				N25E	22	L_1
TR01-189						
TR01-190				N16E	25	L_1
TR01-306						
TR01-307						
TR01-308						
TR01-309						
TR01-310						
TR01-311						
TR01-312	N39E	87SE	S_1			
TR01-313	N4E	85SE	S_1			
TR01-314	N6E	63SE	S_1	N17E	8	L_1
TR01-315	N34E	85NW	S_1	N32E	9	L_1
TR01-316						
TR01-317						
TR01-318	N10W	72NE	S_1			
TR01-319	N2E	69NW	S_1			
TR01-320						
TR01-321						
TR01-322						
TR01-323						
TR01-324						
TR01-325						
TR01-326	N25W	57SW	S_1			
TR01-327	N8E	50NW	S_1			
TR01-328						
TR01-329	N10W	75SW	S_1			
TR01-330						
TR01-331	N6E	55NW	S_1			
TR01-332	N9E	77NW	S_1			
TR01-333	N10E	77NW	S_1			
TR01-334						
TR01-335	N5E	82NW	S_1			
TR01-336						
TR01-337	N8E	79NW	S_1	N32E	10	L_1
TR01-338	N10E	80NW	S_1	S10W	2	L_1
TR01-339						
TR01-340	N40E	5NW				
TR01-341						
TR01-342						
TR01-343	E-W	22N	S_1			
TR01-344						
TR01-345						
TR01-346						
TR01-347						
TR01-348						
TR01-349						
TR01-350	N72E	76SE	S_2			
TR01-351	N63E	72SE	S_2			
TR01-352						
TR01-353						

TR01-242				N45E	5	L_2
TR01-243						
TR01-244	E-W	35N	S_2			
TR01-245						
TR01-246						
TR01-247						
TR01-248						
TR01-300						
TR01-301	N18E	68NW	S_1			
TR01-302						
TR01-303						
TR01-304						
TR01-305						
TR01-370						
TR01-371						
TR01-372						
TR01-373						
TR01-374	N-S	75E	S_2			
TR01-375	N15W	47SW	S_2			
TR01-376						
TR01-377						
TR01-378						
TR01-379	N74W	90	S_2			
TR01-380	N4E	70NW	S_2			
TR01-381						
TR01-382						
TR01-383						
TR01-384						
TR01-385						
TR01-386						
TR01-387						
TR01-388						
TR01-389						
TR01-390	N15W	86NE	S_e			
TR01-391						
TR01-392						
TR01-393						
TR01-394						
TR01-395						
TR01-396						
TR01-397	N80W	13SW	S_e			
TR01-398						
TR01-399						
TR01-400						
TR01-401						
TR01-402						
TR01-403						
TR01-404						
TR01-405	N45E	74SE	S_2			
TR01-406	N40E	74NW	S_2	N85W	85	L_2
TR01-407						
TR01-408	N60E	31NW	S_2			
TR01-409	N50E	80NW	S_2			
TR01-410	N45E	72NW	S_2			
TR01-411	N55E	73NW	S_2			
TR01-412						
TR01-413						
TR01-414	N54E	82SE	S_e			
TR01-415						
TR01-416	N8E	90	S_e			
TR01-417	N85W	90	S_e			

TR01-354	N71E	90	S_2			
TR01-355	N30E	58SE	S_2			
TR01-356						
TR01-357						
TR01-358						
TR01-359						
TR01-360						
TR01-361	N81W	70NE	S_2			
TR01-362	N30E	18NW	S_2			
TR01-363						
TR01-364	N75W	71SE	S_2			
TR01-365						
TR01-366						
TR01-367						
TR01-368						
TR01-369						
TR01-434						
TR01-435	N25W	46SW	S_2			
TR01-436						
TR01-437	N5E	88SE	S_2			
TR01-438						
TR01-439						
TR01-440						
TR01-441						
TR01-442	N13W	78NE	S_e			
TR01-443						
TR01-444						
TR01-445	N68E	74SE	S_e			
TR01-446						
TR01-447						
TR01-448						
TR01-449						
TR01-450						
TR01-451						
TR01-452						
TR01-453						
TR01-454	N48E	90	S_2	N42W	90	L_2
TR01-455	N19E	77NW	S_2	N19W	61	L_2
TR01-456						
TR01-457						
TR01-458	N12E	69SE	S_e			
TR01-459	E-W	67N	S_e			
TR01-460	N35E	81NW	S_e			
TR01-461						
TR01-462	N75E	85SE	S_e			
TR01-463	E-W	75S	S_e			
TR01-464	N70E	68SE	S_e			
TR01-465	N81E	73NW	S_e			
TR01-466	N35E	71NW	S_e			
TR01-467						
TR01-468	N10W	76NE	S_e			
TR01-469						
TR01-470						
TR01-471						
TR01-472	N74E	71NW	S_2			
TR01-473						
TR01-474	N10W	70NE	S_2	N5E	20	L_2
TR01-475						
TR01-476	N80E	74NW	S_e			
TR01-477	N54E	60SE	S_e			
TR01-478	N34E	85SE	S_e			

TR01-418	N80E	44SE	S_e			
TR01-419						
TR01-420	N45E	83SE	S_e			
TR01-421	N2E	62NW	S_e			
TR01-422	N15E	80NW	S_e			
TR01-423						
TR01-424	N57E	70SE	S_e			
TR01-425						
TR01-426						
TR01-427	N10W	56SW	S_2			
TR01-428						
TR01-429						
TR01-430	N9E	56SW	S_2			
TR01-431						
TR01-432						
TR01-433	N1E	25NW	S_2			
TR01-498						
TR01-499						
TR01-500						
TR01-501						
TR01-502	N15E	72NW	S_2			
TR01-503	N2E	59NW	S_2			
TR01-504	N38E	70NW	S_2			
TR01-505	N5E	86SE	S_2			
TR01-506	N5W	52SW	S_2			
TR01-507						
TR01-508	N13W	71NW	S_2			
TR01-509	N32E	59NW	S_2			
TR01-510	N25E	75NW	S_2			
TR01-511	N10E	72NW	S_2			
TR01-512	N12E	79NW	S_2			
TR01-513	N5E	52SE	S_2			
TR01-514						
TR01-515	N10W	82SW	S_2			
TR01-516						
TR01-517	N20E	59SE	S_2			
TR01-518						
TR01-519						
TR01-520	N20E	76SE	S_2			
TR01-521	N20E	75NW	S_2			
TR01-522	N20E	68NW	S_2			
TR01-523						
TR01-524						
TR01-525						
TR01-526						
TR01-527	N8E	63NW	S_2			
TR01-528						
TR01-529						
TR01-530						
TR01-531						
TR01-532						
TR01-533						
TR01-534	N75E	34NW	S_2			
TR01-535						
TR01-536	N11E	60NW	S_2			
TR01-537						
TR01-538						
TR01-539						
TR01-540						
TR01-541	N88E	83NW	S_2			
TR01-542						

TR01-479						
TR01-480						
TR01-481	N45W	35NE	S_e			
TR01-482	N79E	73SE	S_e			
TR01-483						
TR01-484	N-S	75E	S_e			
TR01-485						
TR01-486						
TR01-487						
TR01-488	N60E	65SE	S_e			
TR01-489	N27E	60NW	S_e			
TR01-490						
TR01-491						
TR01-492						
TR01-493						
TR01-494	N15E	13NW	S_e			
TR01-495						
TR01-496						
TR01-497						
TR01-562	N18E	83NW	S_2			
TR01-563						
TR01-564						
TR01-565						
TR01-566						
TR01-567						
TR01-568						
TR01-569	N4E	50NW	S_2			
TR01-570	N32E	72NW	S_2			
TR01-571						
TR01-572						
TR01-573						
TR01-574						
TR01-575						
TR01-576	N30E	73NW	S_e			
TR01-577						
TR01-578						
TR01-579						
TR01-580						
TR01-581						
TR01-582						
TR01-583						
TR01-584						
TR01-585						
TR01-586						
TR01-587						
TR01-588						
TR01-589						
TR01-590						
TR01-591						
TR01-592	N41E	34NW	S_2			
TR01-593						
TR01-594						
TR01-595						
TR01-596						
TR01-597						
TR01-598						
TR01-599						
TR01-600						
TR01-601						
TR01-602						
TR01-603						

TR01-543	N27W	66SW	S_2			
TR01-544						
TR01-545	N2E	76NW	S_2			
TR01-546	N32E	55NW	S_2			
TR01-547	N2E	78NW	S_2			
TR01-548						
TR01-549						
TR01-550	N8E	75SE	S_2			
TR01-551						
TR01-552						
TR01-553	N28E	80SE	S_e			
TR01-554	N20E	70SE	S_e			
TR01-555						
TR01-556						
TR01-557						
TR01-558	N8E	78NW	S_e			
TR01-559	N15W	68SW	S_e			
TR01-560						
TR01-561						
TR01-626	N10E	90	S_1			
TR01-627						
TR01-628	N25E	76NW	S_1			
TR01-629						
TR01-630	N25E	69NW	S_1			
TR01-631						
TR01-632	N6E	76SE	S_1			
TR01-633	N5W	69SW	S_1			
TR01-634	N10W	75NE	S_1			
TR01-635	N10W	77NE	S_1			
TR01-636						
TR01-637	N12E	82NW	S_1			
TR01-638	N17E	85NW	S_1			
TR01-639						
TR01-640	N7E	77NW	S_1			
TR01-641	N20E	61NW	S_1			
TR01-642	N9E	87NW	S_1			
TR01-643	N30W	67SW	S_1			
TR01-644						
TR01-645	N3E	74NW	S_e			
TR01-646	N22W	72NE	S_e			
TR01-647						
TR01-648						
TR01-649						
TR01-650						
TR01-651	N-S	76W	S_1			
TR01-652	N15W	74SW	S_1			
TR01-653						
TR01-654						
TR01-655						
TR01-656						
TR01-657						
TR01-658						
TR01-659						
TR01-660						
TR01-661	N20E	90	S_1			
TR01-662	N12E	85NW	S_1			
TR01-663	N20E	85NW	S_1			
TR01-664	N15E	89NW	S_1			
TR01-665	N12E	83NW	S_1			
TR01-666						
TR01-667						

TR01-604	N10E	68NW	S_2			
TR01-605	N-S	37W	S_2			
TR01-606						
TR01-607						
TR01-608	N26E	47NW	S_2			
TR01-609	N20E	35NW	S_2			
TR01-610	N9E	35SE	S_2			
TR01-611						
TR01-612						
TR01-613						
TR01-614	N30E	68NW	S_2			
TR01-615	N44E	52SE	S_2			
TR01-616	N26E	59NW	S_2			
TR01-617	N20E	59NW	S_2			
TR01-618	N49E	90	S_2			
TR01-619	N46E	80SE	S_2			
TR01-620	N5W	80NE	S_2			
TR01-621						
TR01-622						
TR01-623	N34E	57NW	S_e			
TR01-624						
TR01-625	N47E	54NW	S_1	N47E	5	L_1
TR01-692	N28E	80NW	S_1			
TR01-693	N16E	88NW	S_1			
TR01-694	N18E	85SE	S_1	N18E	13	L_1
TR01-695	N22E	84NW	S_1			
TR01-696	N15E	85SE	S_1			
TR01-697	N16E	83NW	S_1			
TR01-698	N11E	77SE	S_1			
TR01-699	N17E	86NW	S_1			
TR01-700	N20E	75NW	S_1			
TR01-701	N19E	85NW	S_1			
TR01-702	N17E	75NW	S_1	N15E	17	L_1
TR01-703	N16E	83NW	S_1			
TR01-704	N22E	81NW	S_1			
TR01-705	N15E	83SE	S_1			
TR01-706	N25E	82NW	S_1			
TR01-707	N20E	82NW	S_1	N19E	13	L_1
TR01-708						
TR01-709	N15W	67NE	S_1			
TR01-710	N10W	73NE	S_1			
TR01-711	N7E	76SE	S_1			
TR01-712	N17W	85NE	S_1			
TR01-713	N7W	80NE	S_1			
TR01-714	N-S	79E	S_1			
TR01-715	N11E	71SE	S_1			
TR01-716	N2E	80SE	S_1			
TR01-717	N10E	77SE	S_1			
TR01-718						
TR01-719	N17W	67SW	S_1			
TR01-720	N24E	83SE	S_1			
TR01-721	N15E	89SE	S_1			
TR01-722	N21E	80NW	S_1			
TR01-723	N22E	84NW	S_1			
TR01-724						
TR01-725	N15E	76NW	S_1			
TR01-726	N15E	78NW	S_1			
TR01-727	N15E	83NW	S_1			
TR01-728	N15E	72SE	S_1			
TR01-729	N14E	86NW	S_1			
TR01-730	N16E	83NW	S_1			

TR01-668	N13E	88NW	S_1			
TR01-669						
TR01-670						
TR01-671						
TR01-672						
TR01-673	N9W	83NE	S_1			
TR01-674	N2W	80NE	S_1			
TR01-675						
TR01-676						
TR01-677	N12E	81SE	S_1			
TR01-680	N9E	53SE	S_1			
TR01-681	N-S	75E	S_1			
TR01-682	N5E	85SE	S_1			
TR01-683	N40E	88NW	S_1			
TR01-684	N11E	50SE	S_1			
TR01-685	N15E	73NW	S_1			
TR01-686	N14E	60NW	S_1			
TR01-687						
TR01-688	N14E	59NW	S_1			
TR01-689	N16E	89NW	S_1			
TR01-690	N16E	81NW	S_1			
TR01-691	N18E	73NW	S_1			
TR01-756	N5E	76SE	S_1			
TR01-757						
TR01-758						
TR01-759	N13E	82NW	S_1			
TR01-760	N11E	90	S_1	N11E	3	L_1
TR01-761	N17E	76SE	S_1	N15E	11	L_1
TR01-762	N11E	76SE	S_1	N11E	10	L_1
TR01-763						
TR01-764	N10E	78NW	S_1	N12E	11	L_1
TR01-765						
TR01-766						
TR01-767	N11E	72NW	S_1	N11E	11	L_1
TR01-768	N13E	67SE	S_1	N19E	10	L_1
TR01-769	N15E	90	S_1			
TR01-770						
TR01-771						
TR01-772						
TR01-773	N16E	71NW	S_1	N16E	10	L_1
TR01-774	N16E	87NW	S_1			
TR01-775	N15E	70SE	S_1			
TR01-776	N15E	90	S_1			
TR01-777	N27E	72NW	S_1			
TR01-778	N9E	77NW	S_1			
TR01-779	N15E	83NW	S_1			
TR01-780	N5W	85SW	S_1			
TR01-781	N15E	71NW	S_1			
TR01-782	N10W	72SW	S_1			
TR01-783	N-S	83E	S_1			
TR01-784						
TR01-785						
TR01-786	N4W	50SW	S_1			
TR01-787						
TR01-788						
TR01-789	N25E	77SE	S_2			
TR01-790						
TR01-791						
TR01-792						
TR01-793	N8W	85SW	S_2			
TR01-794						

TR01-731	N20E	80NW	S_1			
TR01-732						
TR01-733	N17E	85NW	S_1			
TR01-734	N18E	77NW	S_1			
TR01-735	N25E	80NW	S_1			
TR01-736	N10E	65NW	S_1			
TR01-737	N-S	90	S_1			
TR01-738	N17E	88NW	S_1	N15E	10	L_1
TR01-739	N25E	60NW	S_1	S25W	1	L_1
TR01-740	N10E	72NW	S_1	N15E	3	L_1
TR01-741	N-S	88NW	S_1			
TR01-742	N13E	74NW	S_1	N14E	0	L_1
TR01-743	N20E	65NW	S_1			
TR01-744	N15E	79SE	S_1			
TR01-745	N18E	86NW	S_1			
TR01-746	N12E	80NW	S_1			
TR01-747	N12E	73NW	S_1	N12E	1	L_1
TR01-748	N15E	77NW	S_1			
TR01-749						
TR01-750						
TR01-751	N38E	19NW	S_1			
TR01-752	N16W	29NE	S_1			
TR01-753						
TR01-754						
TR01-755	N16E	65NW	S_1			
TR01-820	N-S	72E	S_1			
TR01-821	N5W	80NE	S_1			
TR01-822	N10W	72NE	S_1			
TR01-823	N15W	87NE	S_1			
TR01-824	N22W	84NE	S_1			
TR01-825						
TR01-826	N3E	77SE	S_1			
TR01-827	N-S	53E	S_1			
TR01-828	N-S	82E	S_1			
TR01-829	N-S	62E	S_1			
TR01-830						
TR01-831	N5E	85SE	S_1			
TR01-832	N6E	79SE	S_1			
TR01-833	N7E	84SE	S_1			
TR01-834	N5E	87SE	S_1			
TR01-835	N4W	82NE	S_1			
TR01-836	N5E	84NW	S_1			
TR01-837	N16E	86NE	S_1			
TR01-838						
TR01-839	N6E	55SE	S_1			
TR01-840	N5W	72NW	S_1			
TR01-841	N6E	90	S_1			
TR01-842	N20E	71SE	S_1			
TR01-843	N22E	78SE	S_1			
TR01-844	N-S	78E	S_1			
TR01-845						
TR01-846						
TR01-847						
TR01-848	N2E	81SE	S_1			
TR01-849	N12E	90	S_1			
TR01-850	N10E	82SE	S_1			
TR01-851	N12E	76SE	S_1			
TR01-852						
TR01-853	N10W	85NE	S_1			
TR01-854						
TR01-855						

TR01-795						
TR01-796	N30E	71SE	S_2			
TR01-797						
TR01-798	N1W	90	S_2			
TR01-799	N-S	88E	S_2			
TR01-800	N2E	79NW	S_2			
TR01-801	N5E	83NW	S_2			
TR01-802	N-S	88W	S_2			
TR01-803						
TR01-804	N5E	88NW	S_2			
TR01-805	N6W	82SW	S_2			
TR01-806	N14E	90	S_2			
TR01-807						
TR01-808						
TR01-809						
TR01-810	N12E	90	S_2			
TR01-811	N30E	90	S_2			
TR01-812	N45E	90	S_2			
TR01-813	N28E	79SE	S_2			
TR01-814	N28E	85NW	S_2			
TR01-815	N38E	76NW	S_2			
TR01-816						
TR01-817						
TR01-818						
TR01-819						
TR01-884						
TR01-885						
TR01-886	N65E	66SE	S_e			
TR01-887	N65E	90	S_e			
TR01-888						
TR01-889						
TR01-890	N28W	50NE	S_e			
TR01-891						
TR01-892						
TR01-893	N75W	25NE	S_e			
TR01-894						
TR01-895						
TR01-896						
TR01-897						
TR01-898						
TR01-899	N15W	53SW	S_2			
TR01-900	N8E	54NW	S_2			
TR01-901	N15E	57NW	S_2			
TR01-902	N8E	48NW	S_2			
TR01-903	N2W	56SW	S_2			
TR01-904	N14W	47SW	S_2			
TR01-905	N35W	40SW	S_2			
TR01-906	N2W	55SW	S_2			
TR01-907	N3E	40NW	S_2			
TR01-908	N10W	44SW	S_2			
TR01-909	N2W	47SW	S_2			
TR01-910	N1E	42NW	S_2			
TR01-911	N8W	45SW	S_2			
TR01-912						
TR01-917						
TR01-918						
TR01-919	N9W	38NE	S_1			
TR01-920						
TR01-921	N20E	45SE	S_1			
TR01-922						
TR01-923						

TR01-856						
TR01-857						
TR01-858	N8E	88SE	S_1			
TR01-859	N12E	82SE	S_1			
TR01-860						
TR01-861	N5W	88NE	S_1			
TR01-862						
TR01-863	N15E	90	S_1			
TR01-864	N5E	90	S_1			
TR01-865						
TR01-866	N5W	66NE	S_1			
TR01-867						
TR01-868	N8E	86SE	S_1			
TR01-869	N12E	59SE	S_1	N12E	16	L_1
TR01-870	N8E	75SE	S_1			
TR01-871	N-S	84E	S_1			
TR01-872	N-S	68E	S_1			
TR01-873	N2E	90	S_1			
TR01-874	N10E	84SE	S_1			
TR01-875	N12W	78NE	S_1			
TR01-876						
TR01-877						
TR01-878						
TR01-879	N75W	74NE	S_e			
TR01-880						
TR01-881	N58E	63SE	S_e			
TR01-882						
TR01-883						
TR01-952						
TR01-953						
TR01-954	N10E	55SE	S_1			
TR01-955						
TR01-956	N5E	87SE	S_1			
TR01-957	N8E	18SE	S_1			
TR01-958	N10W	48NE	S_1			
TR01-959	N2E	26SE	S_1			
TR01-960						
TR01-961						
TR01-962	N30E	69NW	S_1			
TR01-963	N34E	76NW	S_1			
TR01-964						
TR01-965						
TR01-966						
TR01-967	N17E	84SE	S_1			
TR01-968						
TR01-969	N10E	90	S_1			

TR01-924	N25E	85SE	S_1			
TR01-925	N10E	90	S_1			
TR01-926						
TR01-927	N15E	90	S_1			
TR01-928	N15E	62NW	S_1			
TR01-929						
TR01-930						
TR01-931						
TR01-932						
TR01-933	N15W	74NE	S_1			
TR01-934	N5W	79NE	S_1			
TR01-935	N15E	80SE	S_1			
TR01-936	N12E	66NW	S_1			
TR01-937						
TR01-938						
TR01-939	N5E	84SE	S_1			
TR01-940						
TR01-941	N2W	82NE	S_1			
TR01-942	N2E	84SE	S_1			
TR01-943	N17E	90	S_1			
TR01-944						
TR01-945						
TR01-946	N-S	76E	S_1	N12E	10	L_1
TR01-947	N10W	81NE	S_1			
TR01-948						
TR01-949	N28E	90	S_1			
TR01-950						
TR01-951						
TR01-970	N10E	90	S_1			
TR01-971	N25E	81SE	S_1			
TR01-972	N4E	54SE	S_1			
TR01-973	N5E	77SE	S_1			
TR01-1000	N44E	39NW	S_1			
TR01-1001	N10W	85SW	S_1			
TR01-1002	N30E	90	S_1			
TR01-1003						
TR01-1004						
TR01-1005						
TR01-1006						
TR01-1007						
TR01-1008	N22W	90	S_1			
TR01-1009						
TR01-1010						
TR01-1011						
TR01-1012						
TR01-1013						

Appendix B. Fracture data from the Tar River area.

Fracture Data		
Station	Strike	Dip
TR01-309	N10E	72SE
	N15E	75SE
TR01-329	N34W	81NE
	N40W	84NE
	N42W	77NE
TR01-343	N5W	85NE
	N6W	82NE
TR01-355	N50W	85SW
	N48W	80SW
TR01-469	N60W	55SW
	N15W	84SW
	N12W	85NE
TR01-493	N35W	79SW
TR01-560	N-S	69W
TR01-572	N5W	85NE
TR01-660	N75W	75SW
	N25W	50NE
TR01-726	N75W	70SW
	N75W	79SW
TR01-727	N75W	82SW
TR01-809	N32W	70NE
TR01-1000	N70W	77SW
	N70W	63SW
	N66W	78SW
	N50W	90
	N2E	90
	N2E	90
	N85E	85NW
	N81W	90
	N80W	80SW
	N78E	79SE
TR01-1001	N10W	85SW
TR01-1004	N32W	62SW
	N38E	55NW
	N41E	57NW
	N42E	55NW
	N22E	57NW
	N45E	56NW
	N40E	55NW
	N56W	22NE
	E-W	85N
	N15E	50NW
TR01-1005	N60E	52SE
TR01-1010	N60W	60SW
TR01-1011	N40W	45SW

Fracture Data		
Station	Strike	Dip
TR01-1013	N30E	90
	N14E	86NW
	N14W	55NE
	N2E	82SE
	N5E	87SE
	N5E	89SE
	N5W	80NE
	N29W	69NE
	N2W	80NE
	N41W	78NE
	N6E	88SE
	N33E	87SE
	N17W	78NE
	N79W	80NE
	N45W	69NE
	N14E	73NW
	N75W	69SW
	N88E	79SE
	N2W	80SW
	N10E	90
	N75E	77SE
	N8E	90
	N22E	90
	N-S	90

Appendix C. Geochemical data for the Tar River area and Falls Lake terrane samples (Moye 1981; Phelps, 1998).

	TR01-248	TR01-396	TR01-526	WT02-4492	TR01-218	WR99-2891	WT02-3560	FLM-M
SiO_2	65.6	65.3	63.9	64.38	64.8	68.60	48.84	48.70
TiO_2	0.798	0.837	0.885	0.79	0.895	0.70	1.67	1.95
Al_2O_3	15.6	15.9	16.1	16.3	15.70	14.60	13.4	12.30
Fe_2O_3	6.13	5.95	6.36	6.52	5.18	5.50	13.87	14.90
MnO	0.1	0.1	0.15	0.11	0.11	0.11	0.22	0.32
MgO	2.23	2.3	2.31	2.17	1.79	1.96	7.06	6.70
CaO	1.91	2.92	2.5	1.67	4.14	1.70	10.76	10.20
Na_2O	2.28	2.82	3.17	1.62	4.86	2.36	2.11	0.91
K_2O	3.05	3.03	2.8	3.32	1.55	2.92	0.38	0.27
P_2O_5	0.09	0.12	0.12	0.13	0.23	0.08	0.13	0.18
Cr_2O_3				0.01			0.01	
LOI	2.45	0.90	1.60	2.75	0.80	1.55	1.00	1.10
TOTAL	100.40	100.30	100.10	99.89	100.20	100.30	99.48	97.53
Ag	2	1.1	1.8	<1	1.4	1	<1	
As	2	<1	2		<1	<1		
Au	5	4	4	7	7	<2	6	
B	17	<10	14		<10	17		bd
Ba	553	548	471	576	503	694	26.9	51
Be	3	2	3		2	2		
Bi								
Br	<1	1	<1		<1	2		2.7
Cd	2	2	2		2	3		
Ce	71	87	77	83.6	65	77	11.4	21
Co	17.4	15.3	19.6	13.3	5.9	13	41.3	44
Cr	47	67	70		16	54		89
Cs	4.9	6.3	4.5	7	2.1	2.7	0.5	bd
Cu	98.2	69.8	15.4	72	28.9	20.1	141	3.3
Dy				6.16			7.09	
Er				3.47			4.57	
Eu	1.45	1.97	1.73	1.41	2.82	1.4	1.26	1.61
Ga				19			17	
Gd				7.54			6.11	
Ge	<10	<10	<10		<10	<10		
Hf	6.5	6.9	6.5	6	6.9	5.9	3	4.1
Ho				1.22			1.64	
La	42.8	41.4	36.4	40.2	27.1	40.2	3.5	8
Lu	0.55	0.58	0.54	0.55	0.64	0.55	0.71	
Mo	<2	3	<2	<2	3	<2	<2	
Nb	16	19	16	11	8	14	2	bd
Nd	27	51	49	36.8	33	32	11.3	13
Ni	31	33	30	23	9	17	51	41
Pb	38	13	21	19	16	<2	8	4
Pr				10			2.12	
Rb	117	117	110	111	44	89	6.9	bd
Sb	0.6	<0.1	0.2		0.6	<0.1		0.9
Sc	16	16	22		14	12		42.5
Se	1	1	1		2	<1		
Sm	6.83	6.31	6.47	7.5	6.67	6.93	4.2	4.27
Sn				3			1	
Sr	169	194	228	154	389	195	90.2	123
Ta	1.4	<0.5	1.1	0.7	1.4	0.8	<0.5	
Tb	0.6	0.6	1.1	1.14	1.3	1.1	1.11	0.8
Th	12.5	12	9.7	10.1	4	12	0.2	
Tl				0.6			<0.5	
Tm				0.51			0.65	
U	1	1.2	0.2	2.25	3.1	1.7	<0.05	
V	94	100	97	90	101	94	380	396
W	4	4	3	1	2		<1	
Y	32	31	35	27.3	38	37	35.2	44
Yb	3.78	3.08	3.98	3.5	3.68	3.6	4.2	4.34
Zn	119	85.8	101	85	74.5	57.8	172	112
Zr	277	241	254	186	274	207	82	123